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SECTION 8

DIRECT-CURRENT GENERATORS

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8.1 THE DC MACHINE

Applications. The most important role played by the dc generator is the power supply for the important dc motor. It supplies essentially ripple-free power and precisely held voltage at any desired value from zero to rated. This is truly dc power, and it permits the best possible commutation on the motor because it is free of the severe waveshapes of dc power from rectifiers. It has excellent response and is particularly suitable for precise output control by feedback control regulators. It is also well suited for supplying accurately controlled and responsive excitation power for both ac and dc machines.

The dc motor plays an ever-increasing vital part in modern industry, because it can operate at and maintain accurately any speed from zero to its top rating. For example, high-speed multistand steel mills for thin steel would not be possible without dc motors. Each stand must be held precisely at an exact speed which is higher than that of the preceding stand to suit the reduction in thickness of the steel in that stand and to maintain the proper tension in the steel between stands.

General Construction. Figure 8-1 shows the parts of a medium or large dc generator. All sizes differ from ac machines in having a commutator and the armature on the rotor. They also have salient poles on the stator, and, except for a few small ones, they have commutating poles between the main poles.

Former contributors include Thomas W. Nehl and E. H. Myers.

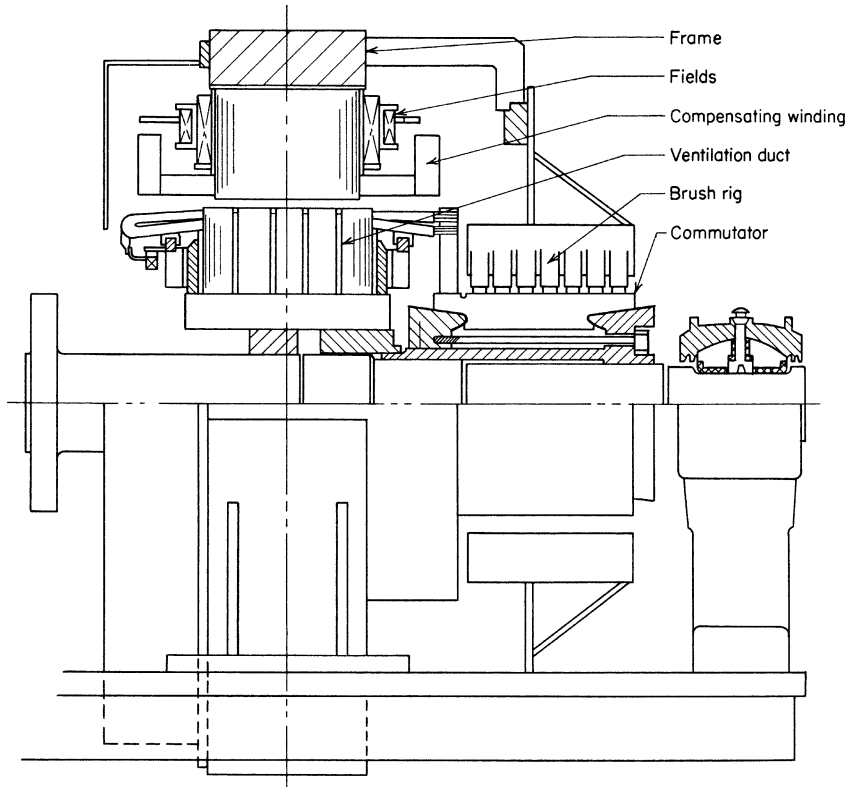


FIGURE 8-1 The dc machine.

Construction and Size. Small dc machines have large surface-to-volume ratios and short paths for heat to reach dissipating surfaces. Cooling requires little more than means to blow air over the rotor and between the poles. Rotor punchings are mounted solidly on the shaft, with no air passages through them.

Larger units, with longer, deeper cores, use the same construction, but with longitudinal holes through the core punchings for cooling air.

Medium and large machines must have large heat-dissipation surfaces and effectively placed cooling air, or “hot spots” will develop. Their core punchings are mounted on arms to permit large volumes of cool air to reach the many core ventilation ducts and also the ventilation spaces between the coil end extensions.

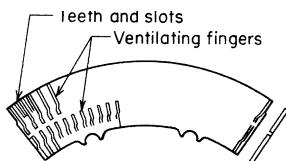


FIGURE 8-2 Armature segment for a dc generator showing vent fingers applied.

Design Components. Armature-core punchings are usually of high-permeability electrical sheet steel, 0.017 to 0.025 in thick, and have an insulating film between them. Small and medium units use “doughnut” circular punchings, but large units, above about 45 inches in diameter, use segmental punchings shaped as shown in Fig. 8-2, which also shows the fingers used to form the ventilating ducts.

Main- and commutating-pole punchings are usually thicker than rotor punchings because only the pole faces are subjected to high-frequency flux changes. These range from 0.062 to 0.125 in thick, and they are normally riveted.

The frame yoke is usually made from rolled mild steel plate, but, on high-demand large generators for rapidly changing loads, laminations may be used. The solid frame has a magnetic time constant of $\frac{1}{2}$ s or more, depending on the frame thickness. The laminated frame ranges from 0.05 to 0.005 s.

The commutator is truly the heart of the dc machine. It must operate with temperature variations of at least 55°C and with peripheral speeds that may reach 7000 ft/min. Yet it must remain smooth concentrically within 0.002 to 0.003 in and true, bar to bar, within about 0.0001 in.

The commutator is made up of hard copper bars drawn accurately in a wedge shape. These are separated from each other by mica plate segments, whose thicknesses must be held accurately for nearly perfect indexing of the bars and for no skew. This thickness is 0.020 to 0.050 in, depending on the size of the generator and on the maximum voltage that can be expected between bars during operation. The mica segments and bars are clamped between two metal V-rings and insulated from them by cones of mica. On very high speed commutators of about 10,000 ft/min, shrink rings of steel are used to hold the bars. Mica is used under the rings.

Carbon brushes ride on the commutator bars and carry the load current from the rotor coils to the external circuit. The brush holders hold the brushes against the commutator surface by springs to maintain a fairly constant pressure and smooth riding.

8.2 GENERAL PRINCIPLES

Electromagnetic Induction. A magnetic field is represented by continuous lines of flux considered to emerge from a north pole and to enter a south pole. When the number of such lines linked by a coil is changed (Fig. 8-3), a voltage is induced in the coil equal to 1 V for a change of 10^8 linkages/s (Mx/s) for each turn of the coil, or $E = (\Delta\phi T \times 10^{-8})/t$ V.

If the flux lines are deformed by the motion of the coil conductor before they are broken, the direction of the induced voltage is considered to be into the conductor if the arrows for the distorted flux are shown to be pointing clockwise and outward if counterclockwise. This is generator action (Fig. 8-4).

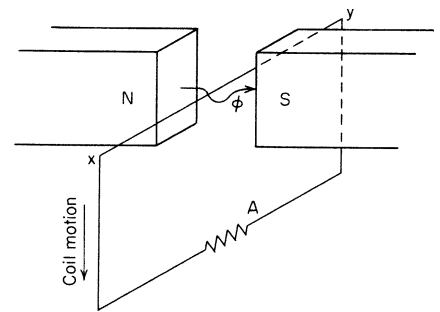


FIGURE 8-3 Generated emf by coil movement in a magnetic field.

Force on Current-Carrying Conductors in a Magnetic Field. If a conductor carries current, loops of flux are produced around it (Fig. 8-5). The direction of the flux is clockwise if the current flows away from the viewer into the conductor, and counterclockwise if the current in the conductor flows toward the viewer.

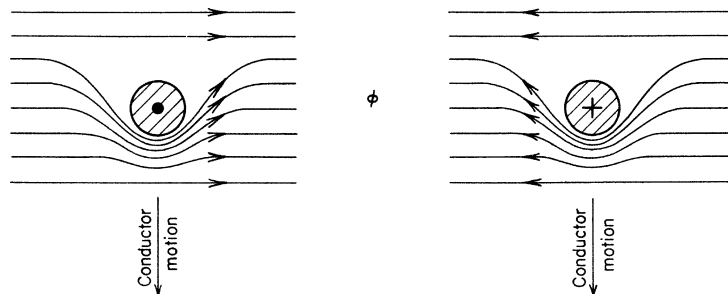


FIGURE 8-4 Direction of induced emf by conductor movement in a magnetic field.

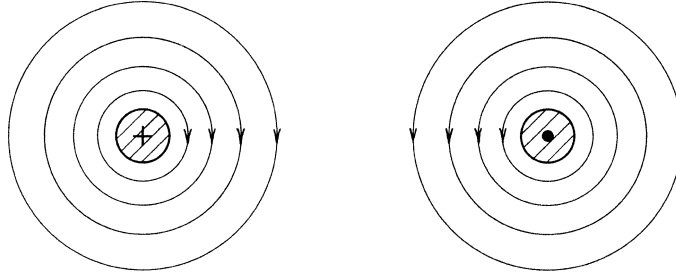


FIGURE 8-5 Magnetic fields caused by current-carrying conductors.

If this conductor is in a magnetic field, the combination of the flux of the field and the flux produced by the conductor may be considered to cause a flux concentration on the side of the conductor, where the two fluxes are additive and a diminution on the side where they oppose. A force on the conductor results that tends to move it toward the side with reduced flux (Fig. 8-6). This is motor action.

Generator and Motor Reactions. It is evident that a dc generator will have its useful voltage induced by the reactions described above, and an external driving means must be supplied to rotate the armature so that the conductor loops will move through the flux lines from the stationary poles. However, these conductors must carry current for the generator to be useful, and this will cause retarding forces on them. The prime mover must overcome these forces.

In the case of the dc motor, the conductor loops will move through the flux, and voltages will be induced in them. These induced voltages are called the “counter emf,” and they oppose the flow of currents which produce the forces that rotate the armature. Therefore, this emf must be overcome by an excess voltage applied to the coils by the external voltage source.

Direct-Current Features. Direct-current machines require many conductors and two or more stationary flux-producing poles to provide the needed generated voltage or the necessary torque. The direction of current flow in the armature conductors under each particular pole must always be correct for the desired results (Fig. 8-7). Therefore, the current in the conductors must reverse at some time while the conductors pass through the space between adjacent north and south poles.

This is accomplished by carbon brushes connected to the external circuit. The brushes make contact with the conductors by means of the commutator.

To describe commutation, the Gramme-ring armature winding (which is not used in actual machines) is shown in Fig. 8-8. All the conductors are connected in series and are wound around a steel ring. The ring provides a path for the flux from the north to the south pole. Note that only the outer portions of the conductors cut the flux as the ring rotates. Voltages are induced as shown. With no external circuit, no currents flow, because the voltages induced in the two halves are in opposition.

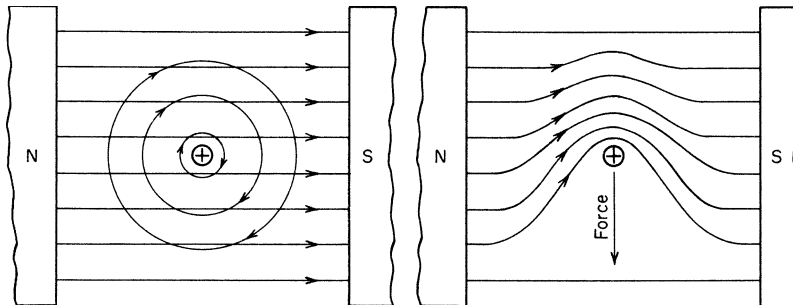


FIGURE 8-6 Force on a current-carrying conductor in a magnetic field.

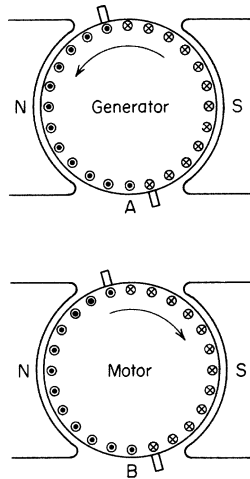


FIGURE 8-7 Direction of current in generator and motor.

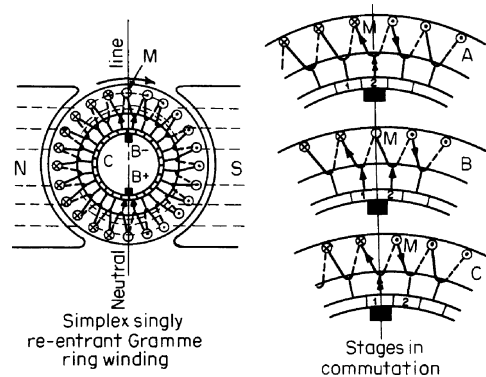


FIGURE 8-8 Principle of commutation.

However, if the coils are connected at a commutator C made up of copper blocks insulated from each other, brushes $B-$ and $B+$ may be used to connect the two halves in parallel with respect to an external circuit and currents will flow in the proper direction in the conductors beneath the poles.

As the armature rotates, the coil M passes from one side of the neutral line to the other and the direction of the current in it is shown at three successive instants at a , b , and c in Fig. 8-9. As the armature moves from a to c and the brush changes contact from segment 2 to segment 1, the current in M is automatically reversed. For a short period, the brush contacts both segments and short circuits the coil. It is important that no voltage be induced in M during that time, or the resulting circulating currents could be damaging. This accounts for the location of the brushes so that M will be at the neutral flux point between the poles.

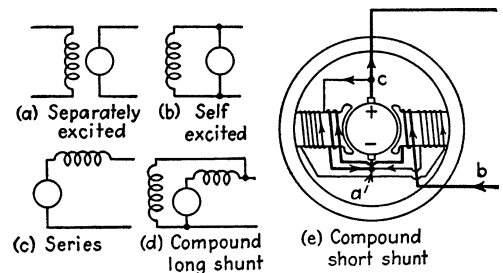


FIGURE 8-9 Methods of excitation.

Field Excitation. Because current-carrying conductors produce flux that links them as described above (in paragraphs on force on current-carrying conductors in a magnetic field), flux from the main poles is obtained by winding conductors around the pole bodies and passing current through them. This current may be supplied in different ways. When a generator supplies its own exciting current, it is "self-excited." When current is supplied from an external source, it is "separately excited." When excited by the load current of the machine, it is "series excited."

8.3 ARMATURE WINDINGS

Terms. The Gramme-ring winding is not used, because half the conductors (those on the inside of the ring) cut no flux and are wasted. Figures 8-8, 8-10, and 8-11 show such windings only because they illustrate types of connections so well.

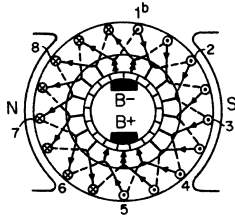


FIGURE 8-10 Singly reentrant duplex winding.

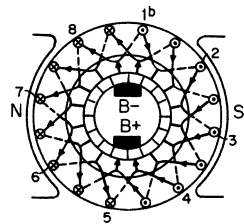


FIGURE 8-11 Doubly reentrant duplex winding.

A *singly reentrant winding* closes on itself only after including all the conductors, as shown in Figs. 8-8 and 8-10.

A *doubly reentrant winding* closes on itself after including half the conductors, as shown in Fig. 8-11.

As shown, a *simplex winding* has only two paths through the armature from each brush (Fig. 8-8). A *duplex winding* has twice as many paths from each brush and is shown in Figs. 8-10 and 8-11. Note that each brush should cover at least two commutator segments with a duplex winding, or one circuit will be disconnected at times from the external circuit. Although it is possible to use multiplex and multiple reentrant windings, they are uncommon in the United States. They are used in Europe in some large machines.

Modern dc machines have the armature coils in radial slots in the rotor. Nonmetallic wedges restrain the coils normally, but some wedgeless rotors use nonmetallic banding around the core, such as glass fibers in polyester resin. This permits shallower slots and helps to reduce commutation sparking. However, the top conductors are near the pole faces and may have high eddy losses. The coil ends outside the slots are held down on coil supports by glass polyester bands for both types.

Multiple, or Lap, Windings. Figure 8-12 shows a *lap-winding coil*. The conductors shown on the left side lie in the top side of the rotor slot. Those on the right side lie in the bottom half of another slot approximately one pole pitch away. At any instant the sides are under adjacent poles, and voltages induced in the two sides are additive. Other coil sides fill the remaining portions of the slots. The coil leads are connected to the commutator segments, and this also connects the coils to form the armature winding. This is shown in Fig. 8-13. The pole faces are slightly shorter than the rotor core.

Almost all medium and large dc machines use simplex lap windings in which the number of parallel paths in the armature winding equals the number of main poles. This permits the current per path to be low enough to allow reasonable-sized conductors in the coils.

Windings. Representations of dc windings are necessarily complicated. Figure 8-14 shows the lap winding corresponding to the Gramme-ring winding of Fig. 8-8. Unfortunately, the nonproductive end portions are emphasized in such diagrams, and the long, useful portions of the coils in the core slots are shown as radial lines. Conductors in the upper layers are shown as full lines, and those

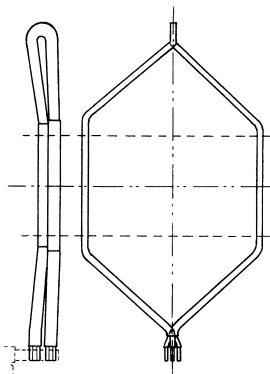


FIGURE 8-12 Coil for one-turn lap winding.

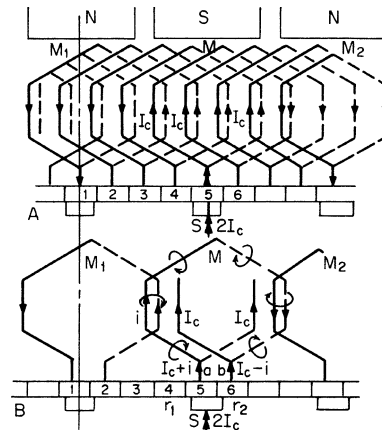


FIGURE 8-13 Multiple, or lap, winding.

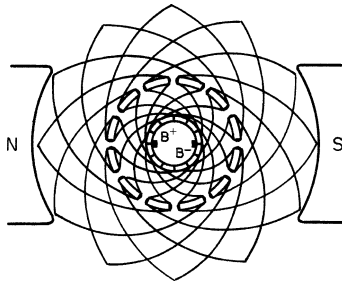


FIGURE 8-14 Simplex lap winding.

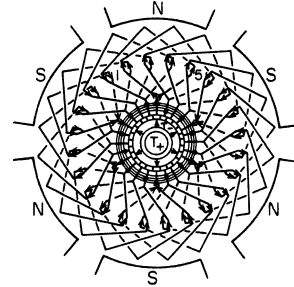


FIGURE 8-15 Simplex singly reentrant full-pitch multiple winding with equalizers.

in the lower layers as dotted lines. The inside end connections are those connected to the commutator bars. For convenience, the brushes are shown inside the commutator.

Note that both windings have the same number of useful conductors but that the Gramme-ring winding requires twice the number of actual conductors and twice the number of commutator bars.

Figure 8-15 shows a 6-pole simplex lap winding. Study of this reveals the six parallel paths between the positive and negative terminals. The three positive brushes are connected outside the machine by a copper ring $T+$ and the negative brushes by $T-$.

The two sides of a lap coil may be full pitch (exactly a pole pitch apart), but most machines use a short pitch (less than a pole pitch apart), with the coil throw one-half slot pitch less than a pole pitch. This is done to improve commutation.

Equalizers. As shown in Fig. 8-15, the parallel paths of the armature circuit lie under different poles, and any differences in flux from the poles cause different voltages to be generated in the various paths. Flux differences can be caused by unequal air gaps, by a different number of turns on the main-pole field coils, or by different reluctances in the iron circuits.

With different voltages in the paths paralleled by the brushes, currents will flow to equalize the voltages. These currents must pass through the brushes and may cause sparking, additional losses, and heating. The variation in pole flux is minimized by careful manufacture but cannot be entirely avoided.

To reduce such currents to a minimum, copper connections are used to short-circuit points on the paralleled paths that are supposed to be at the same voltage. Such points would be exactly two pole pitches apart in a lap winding. Thus in a 6-pole simplex lap winding, each point in the armature circuit will have two other points that should be at its exact potential. For these points to be accessible, the number of commutator bars and the number of slots must be a multiple of the number of poles divided by 2.

These short-circuited rings are called "equalizers." Alternating currents flow through them instead of the brushes. The direction of flow is such that the weak poles are magnetized and the strong poles are weakened. Usually, one coil in about 30% of the slots is equalized. The cross-sectional area of an equalizer is 20% to 40% that of the armature conductor.

Involute necks, or connections, to each commutator bar from conductors two pole pitches apart give 100% equalization but are troublesome because of inertia and creepage insulation problems.

Figure 8-15 shows the equalizing connections behind the commutator connections. Normally they are located at the rear coil extensions, and so they are more accessible and less subject to carbon-brush dust problems.

Two-Circuit, or Wave, Windings. Figure 8-16 shows a wave type of coil. Figure 8-17 gives a 6-pole wave winding. Study reveals that it has only two parallel paths between the positive and negative terminals. Thus, only two sets of brushes are needed. Each brush shorts $p/2$ coils in series. Because points a , b , and c are at the same potential (and, also, points d , e , and f), brushes can be placed at each of these points to allow a commutator one-third as long.

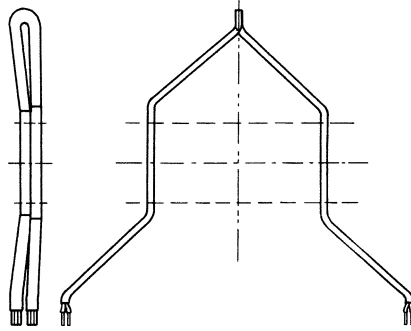


FIGURE 8-16 One-turn wave winding.

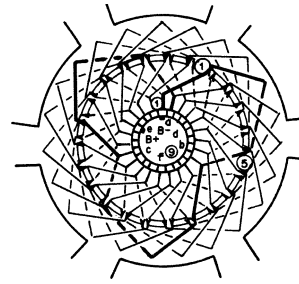


FIGURE 8-17 Two-circuit progressive winding.

The winding must progress or retrogress by one commutator bar each time it passes around the armature for it to be singly reentrant. Thus, the number of bars must equal $(kp/2) \pm 1$, where k is a whole number and p is the number of poles. The winding needs no equalizers because all conductors pass under all poles.

Although most wave windings are 2-circuit, they can be multicircuit, as 4 or 16 circuits on a 4-pole machine or 6, 12, or 24 circuits on a 12-pole machine. Multicircuit wave windings with the same number of circuits as poles can be made by using the same slot and bar combinations as on a lap winding. For example, with an 8-pole machine with 100 slots and 200 commutator bars, the bar throw for a simplex lap winding would be from bar 1 to bar 2 and then from bar 2 to bar 3, etc. For an 8-circuit wave winding, the winding must fail to close by circuits/2 bars, or 4. Thus, the throw would be bar 1 to 50, to bar 99, to bar 148, etc. The throw is $(\text{bars} \pm \text{circuits}/2)(p/2)$, in this case, $(200 - 4)/4 = 49$. Theoretically such windings require no equalizers, but better results are obtained if they are used.

Since both lap and multiple wave windings can be wound in the same slot and bar combination simultaneously, this is done by making each winding of half-size conductors. This combination resembles a *frog's leg* and is called by that name. It needs no equalizers but requires more insulation space in the slots and is seldom used.

Some wave windings require *dead coils*. For instance, a large 10-pole machine may have a circle of rotor punchings made of five segments to avoid variation in reluctance as the rotor passes under the five pairs of poles. To avoid dissimilar slot arrangements in the segments, the total number of slots must be divisible by the number of segments, or 5 in this case. This requires the number of commutator bars to be also a multiple k of 5. However, the bar throw for a simplex wave winding must be an integer and equal to $(\text{bars} \pm 1)(p/2)$. Obviously $(5k \pm 1)/5$ cannot meet this requirement. Consequently one coil, called a *dead coil*, will not be connected into the winding, and its ends will be taped up to insulate it completely. No bar will be provided for it, and thus the bar throw will be an integer. Dead coils should be avoided because they impair commutation.

8.4 ARMATURE REACTIONS

Cross-Magnetizing Effect. Figure 8-18a represents the magnetic field produced in the air gap of a 2-pole machine by the mmf of the main exciting coils, and part *b* represents the magnetic field produced by the mmf of the armature winding alone when it carries a load current. If each of the Z armature conductors carries I_a , then the mmf between *a* and *b* is equal to ZI_a/p At. That between *c* and *d* (across the pole tips) is $\psi ZI_a/p$ At, where ψ = ratio of pole arc to pole pitch. On the assumption that all the reluctance is in the air gap, half the mmf acts at *ce* and half at *fd*, and so the cross-magnetizing effect at each pole tip is

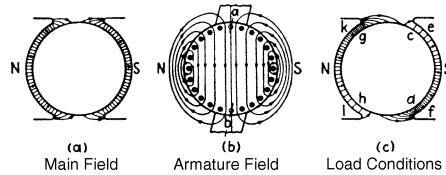


FIGURE 8-18 Flux distribution in (a) main field, (b) armature field, and (c) load conditions.

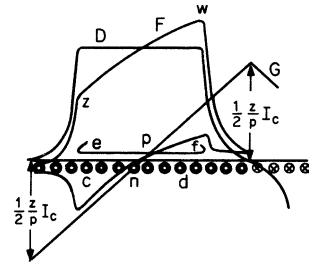


FIGURE 8-19 Flux distribution in a large machine with p poles.

$$\frac{\psi Z I_c}{2p} \text{ ampere-turns} \quad (8-1)$$

for any number of poles.

Field Distortion. Figure 8-18c shows the resultant magnetic field when both armature and main exciting mmfs exist together; the flux density is increased at pole tips d and g and is decreased at tips c and h .

Flux Reduction Due to Cross-Magnetization. Figure 8-19 shows part of a large machine with p poles. Curve D shows the flux distribution in the air gap due to the main exciting mmf acting alone, with flux density plotted vertically. Curve G shows the distribution of the armature mmf, and curve F shows the resultant flux distribution with both acting. Since the armature teeth are saturated at normal flux densities, the increase in density at f is less than the decrease at e , so that the total flux per pole is diminished by the cross-magnetizing effect of the armature.

Demagnetizing Effect of Brush Shift. Figure 8-20 shows the magnetic field produced by the armature mmf with the brushes shifted through an angle θ to improve commutation. The armature field is no longer at right angles to the main field but may be considered the resultant of two components, one in the direction OY , called the “cross-magnetizing component,” and the other in the direction OX , which is called the “demagnetizing component” because it directly opposes the main field. Figure 8-21 gives the armature divided to show the two components, and it is seen that the demagnetizing ampere-turns per pair of poles are

$$\frac{Z I_c}{p} \times \frac{2\theta}{180} \text{ ampere-turns} \quad (8-2)$$

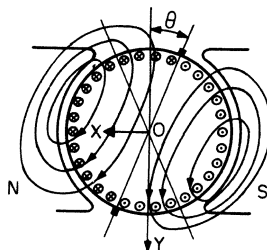


FIGURE 8-20 Demagnetizing effect.

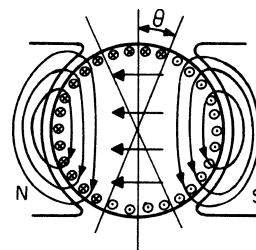


FIGURE 8-21 Cross-magnetizing effect.

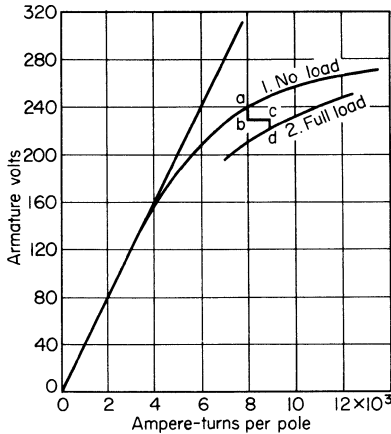


FIGURE 8-22 Saturation curves—dc generator.

where $2\theta/180$ is about 0.2 for small noncommutating pole machines where brush shift is used. The demagnetizing ampere-turns per pole would be

$$0.1ZI_c/p \text{ ampere-turns} \quad (8-3)$$

No-Load and Full-Load Saturation Curves. Curve 1 of Fig. 8-22 is the no-load saturation curve of a dc generator. When full-load current is applied, there is a decrease in useful flux, and therefore a drop in voltage ab due to the armature cross-magnetizing effect (see paragraph on flux reduction, above). A further voltage drop from brush shift is counterbalanced by an increase in excitation $bc = 0.1ZI_c/p$; also a portion cd of the generated emf is required in overcoming the voltage drop from the current in the internal resistance of the machine. The no-load voltage of 240 V requires 8000 At. At full load at that excitation the terminal voltage drops to 220 V. To have both no-load and full-load voltages equal to 240 V, a series field of $10,700 - 8000 = 2700$ At would be required.

8.5 COMMUTATION

Commutation Defined. The voltages generated in all conductors under a north pole of a dc generator are in the same direction, and those generated in the conductors under a south pole are all in the opposite direction (Fig. 8-23). Currents will flow in the same direction as induced voltages in generators and in the opposite direction in motors. Thus, as a conductor of the armature passes under a brush, its current must reverse from a given value in one direction to the same value in the opposite direction. This is called “commutation.”

Conductor Current Reversal. If commutation is “perfect,” the change of the current in a coil will be linear, as shown by the solid line in Fig. 8-24. Unfortunately, the conductors lie in steel slots, and self- and mutual inductances in Fig. 8-25 cause voltages in the coils short-circuited by the brushes. These result in circulating currents that tend to prevent the initial current change, delaying the reversal. In extreme cases, the delay may be as severe as indicated by the dotted line of Fig. 8-24. Because the current must be reversed by the time the coil leaves the brush (when there is no longer any path for circulating currents), the current remaining to be reversed at F must discharge its energy in an

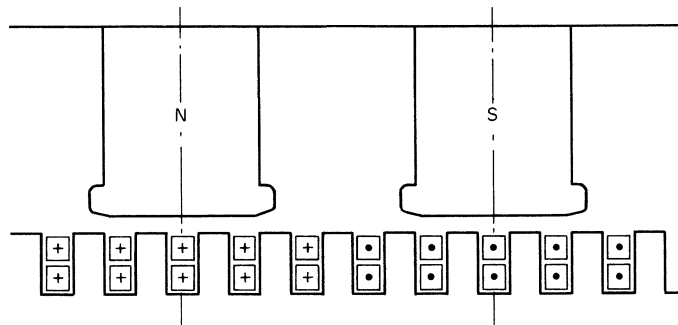


FIGURE 8-23 Conductor currents.

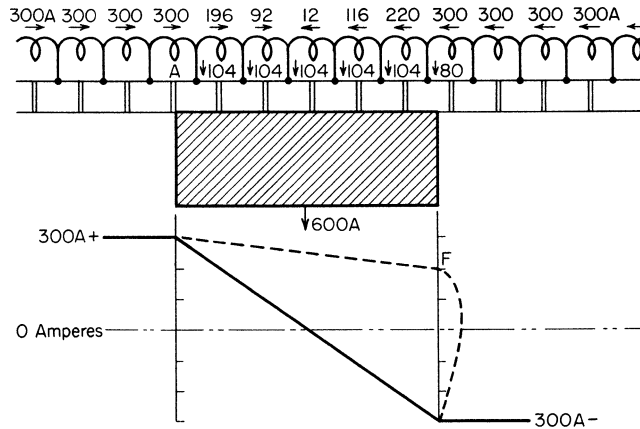


FIGURE 8-24 Commutation.

electric arc from the commutator bar to the heel of the brush. This is commutation sparking. It can burn the edges of the commutator bars and the brushes. However, most large and heavy-duty dc machines have some nondamaging sparking, and “sparkless” commutation is not required by accepted standards. However, commutation must not require undue maintenance.

The undesired voltages causing the circulating currents result from interpolar fluxes from armature reaction, leakage fluxes of the current-carrying armature conductors, and, in some cases, main-pole-tip spray flux. Beneficial factors reducing the circulating currents include the resistance of the short-circuited coil, the resistance of the commutator risers, and that of the brush body to transverse currents. However, the most important factor is the voltage drop at the sliding contact between the brush face and the copper commutator surface.

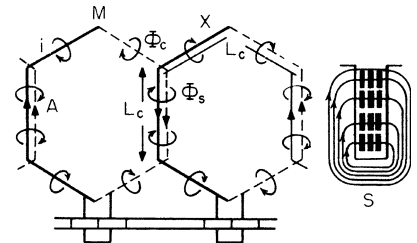


FIGURE 8-25 Magnetic field surrounding short-circuited coils.

Commutator Brushes. Most dc machines use electrographitic brushes with about 60 A/in² current density at full load. These have an essentially constant contact voltage drop at the commutator surface of about 1 V for loads above one-third. This effective resistance to circulating currents is important to good operation of dc machines.

The cross-resistance of the brush body to circulating currents can be increased by splitting the brush into two wafers and making the crosscurrents cross the air gap between the two pieces. This has increased the good commutation range on some machines by 7%. The use of double brush holders, which have metal dividers between two brushes in the holder, is even more effective and has increased the good commutation range as much as 15% over single solid brushes.

Unless special brushes are used, machines should be operated for not more than a few hours at a time at brush densities below 30 A/in². If this is done, the commutator surface develops a hard glaze which makes the brushes chatter. This results in frayed shunts, chipped and broken brushes, and excessive brush-finger wear.

Reactance Voltage of Commutation. The sum of the voltages induced in the armature coil while it is short-circuited by the brushes while undergoing commutation is called the *reactance voltage of commutation*. One of the most important of the fluxes causing this voltage is the *slot-leakage flux* shown in

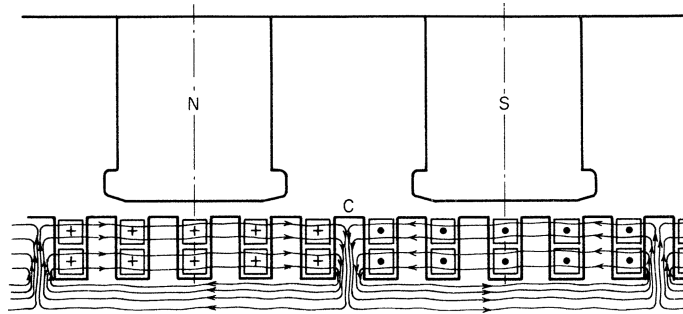


FIGURE 8-26 Slot-leakage flux.

Fig. 8-26. This is the resultant flux leakage from current in the individual slot conductors, as shown in Fig. 8-25. Because the radial fluxes in the rotor teeth from adjacent slot conductors essentially cancel except at point *C* (the point of current reversal), the resultant flux is as shown in Fig. 8-26. As the conductors commutate and pass through *C*, they cut the flux shown there and this generates the *reactance voltage of commutation*. Actually, part of this voltage is also due to leakage-flux changes at the coil ends, to armature reaction flux, etc., but, for simplicity, only the important slot leakage flux is shown.

Commutating Poles. The beneficial factors that limit the circulating currents in coils being commutated are not adequate to prevent serious delays in current reversal. Other means must be taken to prevent sparking.

If the flux at *C* (Fig. 8-26) could be nullified by an equal flux in the opposite direction, the circulating currents due to the slot leakage flux would be prevented.

The location of *C* is fixed by the location of the brushes. If the brushes were shifted toward the south main pole, a position could be found where the main flux upward into the south pole would cancel the downward flux due to slot leakage at *C*.

This method was used in the early history of dc machines. Unfortunately, the slot-leakage flux at *C* is proportional to conductor load current, whereas the flux into the south pole is not. Thus, a new brush position is needed for every change in load current.

A better solution is to provide stationary poles midway between the main poles, as shown in Fig. 8-27. Windings on these *commutating poles* carry the load current. Thus, the flux into the pole at *C* is proportional to the rotor conductor currents and, theoretically, can cancel the voltages induced in the coils being commutated by the slot leakage flux. In the case of the dc motor, the current

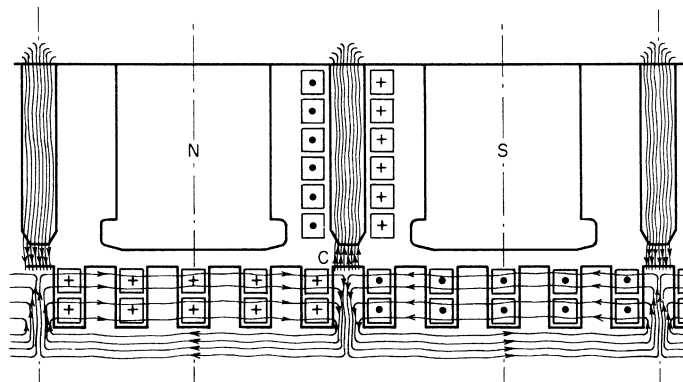


FIGURE 8-27 Slot-leakage flux and commutating-pole flux.

reverses in both the armature and the commutating field, and proper canceling is maintained.

Note that the strength of the commutating-pole winding must be greater than the armature-winding ampere-turns per pole by the amount required to carry the needed flux across the commutating-pole air gap.

Almost all modern dc machines use commutating poles, although some small machines have only half as many as main poles.

The commutating-pole tip is usually shaped with tapered sides to approximate the shape of the reactance voltage of commutation form (see Figs. 8-27 and 8-28).

Reactance Voltage of Commutation Formula. To determine the useful flux needed across the commutating-pole air gap, it is useful to calculate the reactance voltage of commutation (the total of the voltages induced in the armature coil as it undergoes commutation). The approximate value of this voltage may be calculated by the use of the following formula:

$$E_c = \frac{\text{poles}}{\text{paths}} (l_c Z T) (\text{r/min}) (10^{-10}) \left[(K_r L_r) + K_2 (PP) (4.5 + 0.2 t_s) + \frac{L_r}{b_s} (3 d_s + 2 SP) \right] \text{ volts} \quad (8-4)$$

where I_c = current per armature conductor, A
 Z = total no. of armature conductors
 T = no. of turns/coil between commutator bars
 L_r = gross armature-core length, in
 K_1 = 18.5 for noncommutating-pole machines
 $= 0$ for machines with commutating-pole length = L_r
 K_2 = 1.0 for machines using nonmagnetic bands
 $= 1.7$ for machines using magnetic bands
 PP = pole pitch, in
 t_s = coil throw, slots
 b_s = width of slot, in
 d_s = depth of slot, in
 SP = slot pitch, in

This formula is based on the work by Lamme. (See Theory of Commutation by B. G. Lamme, *Trans. AIEE*, Oct. 1911, vol. 30.)

The Commutating Zone. This is defined as that space on the armature periphery through which a given slot moves while all the conductors lying in the slot commute. In chorded windings, it is extended to include the coil edges in the chorded slots. The commutating zone thus depends on the number of commutating bars covered per brush.

The zone may be calculated by the following formula:

$$CZ = \frac{SP[(B/S) + (B/S \times Ch) + (B/Br) - Cir/p]}{B/S} \quad (8-5)$$

where CZ is the commutating zone in inches, SP the rotor slot pitch in inches, B/S the number of commutator bars per slot, Ch the slot chording as a fraction of the slot pitch, B/Br the number of commutator bars spanned per brush, Cir the number of paralleled circuits in the armature, and p the number of main poles.

Consider an 8-pole simplex lap winding with three bars per slot, chording of $1/2$ slot, $3\frac{1}{2}$ bars per brush, and slot pitch of 1.05 in:

$$CZ = \frac{1.05 \times (3 + 1\frac{1}{2} + 3\frac{1}{2} - 8/8)}{3} = 2.44 \text{ in}$$

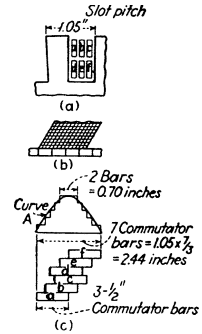


FIGURE 8-28 Commutating zone.

In this machine, all the conductors in a slot are commutated while the armature periphery moves 2.44 in.

This can be seen graphically in Fig. 8-28, where (a) shows a slot with six conductors, (b) shows a brush covering $3\frac{1}{2}$ bars, and (c) shows the graphical solution. In (c) the rectangle *a* represents as abscissa the space of $3\frac{1}{2}$ commutator bars if they were at the armature surface. This is the length to commute coil *a*. The ordinate represents to a convenient scale the commutation voltage induced in this conductor while it is being commutated. Rectangles *b* and *c* are the same for coils *b* and *c*. Since *b* commutates 1 bar later than *a*, it is shown one bar space to the right of *a*, etc. In a similar manner *d*, *e*, and *f* are shown. Normally *d* would be expected to start commutation at the same time as *a*, but, because of chording, it starts later, in this case $1\frac{1}{2}$ bars later. Thus, the commutating zone starts with the beginning of rectangle *a* and is completed at the end of rectangle *f*. On adding the spaces of the parts, this is $3\frac{1}{2}$ bars for *f*, 2 bars for the steps of *e* and *d*, and $1\frac{1}{2}$ bars for chording, or a total of 7 bars at the rotor surface, which is $1.05\frac{2}{3}$, or 2.44 in.

The summation of the individual rectangles as smoothed off by curve *A* of (c) is a rough representation of the reactance voltages induced in the coils during commutation.

Single Clearance. The centerline of the commutating zone and curve *A* of Fig. 8-28 lie midway between the adjacent main-pole tips if the brushes are not shifted off neutral. The arc on the rotor surface between the tips of adjacent main poles is called the *neutral zone*. If the commutating zone is centered in this arc, the spaces left at each end are called the *single clearance*. Thus, the single clearance is

$$SC = (\text{neutral zone} - \text{commutating zone})/2 \quad (8-6)$$

The single clearance is an indication of the probability that spray flux from the main-pole tips might flow into the commutating zone. Such flux would not vary with load and would distort the form of the useful flux from the commutating pole. The commutating-pole useful flux form should closely resemble that of curve *A* in Fig. 8-28.

Noncompensated dc machines usually have main-pole tips with short radial dimensions and have limited spray flux into the neutral zone. The minimum single clearance for these should be not less than 0.6 in and not less than 0.9 in with commutation voltages above 3 or 4 V.

Compensated-machine main poles usually have tips 2 to 3 in deep to accommodate the compensating slots and are more likely to spray flux into the commutating zone. These require single-clearance minimums of 1.2 to 1.4 in.

If there is any question about tip flux reaching the commutating zone, flux plots should be made.

Commutating-Pole Excitation. Figures 8-18*b* and 8-19 show that flux should normally be expected in the commutation area. It is caused by the armature-winding ampere-turns per pole. It could be reduced to zero if the commutating pole had ampere-turns equal and opposite to those of the armature winding. This is $ZI_c/2p$ At/pole.

However, it is necessary that the commutating winding also produces useful flux across the commutating-pole gap to counteract the reactance voltage of commutation, as shown in Fig. 8-27. For this reason, the strength of the commutating field is usually 20% to 30% greater than the armature ampere-turns per pole. This difference is called the *excess ampere-turns*. These must be added to the circled dotted-line bar diagram of Fig. 8-29. The actual flux across the gap is set accurately during the factory test by adjusting the number of sheet-steel shims behind the commutating poles to set the reluctance of the gap for the exact flux needed.

Calculation of Commutating-Pole Air Gaps. With fixed excess ampere-turns on the commutating-pole winding and a certain commutation voltage at rated current and speed, only one particular commutating-pole air gap will result in the most favorable compensation of the commutation voltage. The shape of the pole tip will determine the form of the flux density under it, but the length of the air gap will determine the magnitude of the density.

To counteract the reactance voltage of commutation E_c , the approximate maximum flux density needed in the commutating-pole air gap is

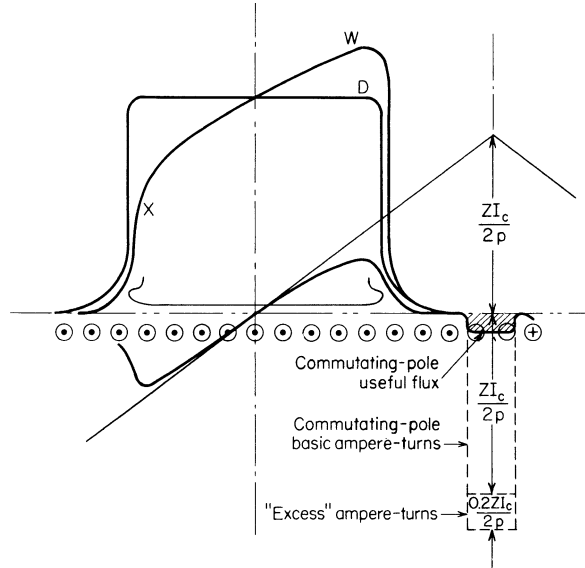


FIGURE 8-29 Commutating-pole ampere-turns.

$$B_m = \frac{E_c \times 23 \times 10^8}{Z/\text{bar} \times DL_c \times r/\text{min}} \quad (8-7)$$

where E_c is the full-load reactance voltage of commutation at speed r/min , Z is the total number of armature conductors, bar is the total number of commutator bars, D is the armature diameter in inches, L_c is the axial length of the commutating poles in inches, and r/min is the revolutions per minute for which E_c was calculated.

The approximate length of the needed commutating-pole single air gap may be calculated by the following formula:

$$\text{Gap} = \frac{3.19 \times \text{excess ampere-turns}}{B_m} \quad (8-8)$$

When the machine is on factory test, the excess ampere-turns can be adjusted to obtain the best commutation possible by placing another dc generator or a battery across the commutating winding to add to the load current flowing in it or to lower the excess by shunting out some of the load current. This is known as a "boost or buck" test. Afterward the commutating-pole air gap is changed to produce the "best" gap flux density with the actual excess ampere-turns. The new gap will be

$$\text{Gap}_2 = \frac{\text{excess At}_1}{\text{excess At}_2} \times \text{gap}_1 \quad (8-9)$$

Dimensions of Commutating Poles. If the useful flux across a commutating-pole air gap is not proportional to the machine load current, the compensation of the reactance voltage of commutation will not be correct for all loads and sparking may damage the brushes and commutator. Thus, the commutating pole must not saturate at the highest load currents to be accommodated. The base of the pole must carry not only the useful air-gap flux but also leakage fluxes from the commutating and main field coils which are near. These leakage fluxes are relatively large and must be determined with care by flux plotting if the danger of commutating-pole saturation exists.

The amount of leakage flux through the base of the pole depends on the length of the leakage paths, the number of coil ampere-turns, and the location of the commutating field. The leakage paths should be made as long as feasible, the coil ampere-turns as few as reasonable, and the commutating coil located as close to the pole tip as possible. Also, all sections of the commutating pole should be large enough to accommodate their flux.

For a normal compensated machine, the leakage flux will be about 75% of the commutating-pole useful flux, or about 140% of the useful flux in a noncompensated machine.

The approximate useful flux can be calculated by using the maximum commutating-pole air-gap flux density from Eq. (8-7). The average flux density of the commutating zone will be approximately

$$B_a = 0.83B_m \quad (8-10)$$

The flux density at overload in the base of the pole is

$$B_{cp} = \frac{K_3 \times K_4 \times B_a \times CZ}{L_c \times W_c} \quad (8-11)$$

where K_3 is 1.75 for compensated machines and 2.40 for noncompensated machines, K_4 is the ratio of overload current to rated current, B_a is the average flux density in the commutating zone, CZ is the width of the commutating zone, L_c is the axial length of the commutating pole, and W_c is the circumferential width of the pole at its base. B_{cp} should not exceed 80,000 to 90,000 lines/in² for good commutation.

Compensating Windings. Although the commutating pole is a good solution for commutation, it does not prevent distortion of the main-pole flux by armature reaction. The flux set up across the main-pole face by the armature mmf is shown in Fig. 8-30*a*. If the pole face is provided with another winding, as shown in Fig. 8-30*b*, and connected in series with the load, it can set up an mmf equal and opposite to that of the armature. This would tend to prevent distortion of the air-gap field by armature reaction. Such windings are called *compensating windings* and are usually provided on medium-sized and large dc machines to obtain the best possible characteristics. They are also often needed to make machines less susceptible to flashovers.

The use of compensating windings reduces the number of turns required on the commutating-pole fields, and this materially reduces the leakage fluxes of the field and, in turn, the pole saturations at high currents. The ampere-turns on the commutating field are reduced by about 50% with the use of a compensating field. This new winding may be considered to be some of the turns taken off the commutating-pole winding and relocated in slots in the main-pole faces.

The number and location of the compensating slots must be carefully chosen to match, as closely as possible, the rotor ampere-turns per inch. However, the slot spacing must not correspond closely to that of the rotor. This would cause a major change in reluctance to the main-pole useful flux every time the rotor moved from a position where the rotor and stator slots all coincided to where the rotor slots coincided with the stator teeth. This would occur once for every slot-pitch movement. The resulting rapid changes in useful flux would cause ripples in the output voltage and also serious magnetic noise. If too few slots are used, local flux distortions occur and the compensating winding loses some of its effectiveness (see Fig. 8-32).

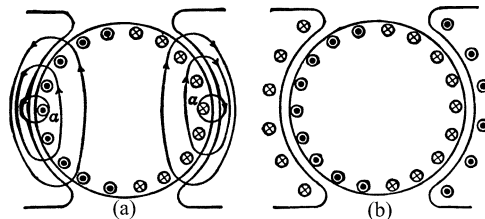


FIGURE 8-30 Armature field without (a) and with (b) compensating windings.

Compensation of armature reaction effectively reduces the armature circuit inductance. This makes the machine less susceptible to the bad effects of $L(di/dt)$ voltages caused by very fast load current changes.

During manufacture, it is possible to locate the compensating winding nonsymmetrically about the centerline of the main pole. This causes a direct-axis flux, which will give a series field effect (Fig. 8-31). For generator cumulative compounding, the slots must be shifted in the direction of the machine rotation. This shift gives a motor differential compounding. The effect cannot be adjusted after manufacture. It seldom exceeds $\frac{1}{2}$ in, and this does not materially reduce the effectiveness of the compensation.

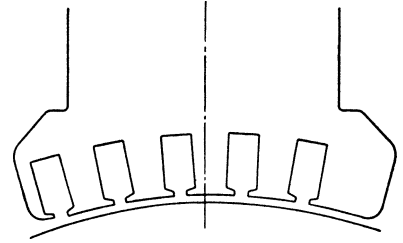


FIGURE 8-31 Offset compensating winding.

Volts per Bar. The mica thickness between the commutator segments depends on the machine design and varies from 0.020 in on small machines to 0.050 in on large units. Although several hundred volts would normally be required to jump these distances, the presence of ionized air from sparking and the presence of conducting carbon dust make it necessary that the voltage between segments be held to low values. If a low-resistance arc does jump between segments, it raises the voltages across the remaining bars. It also tends to ionize some air to form conducting paths across the rest of the bars. If this progresses until all the segments between brush arms of opposite polarity are bridged, then a *flashover* occurs and severe damage may result to the commutator, brushes, and brush holders.

Because the highest voltage between bars is the “trigger” that starts the flash, this is an important limit. The “average” volts per bar has little significance. Figure 8-29 shows that the maximum volts per bar depends on the field form. For the noncompensated machine shown, the maximum volts between segments exists at w . The segments connected to conductors at x have much less voltage between them, and those beyond the edge of the pole have almost none.

The relation between maximum volts per bar and the average depends on the armature ampere-turns per pole and the saturation curve of the gap and teeth at the pole tips. On neglecting the small voltage drop in the series and commutating windings, the voltage between brush arms is the machine voltage V , and the number of bars between arms is B/p . Thus

$$\text{Average volts/bar} = \frac{V \times p}{B} \quad (8-12)$$

where B is the total number of commutator bars and p the number of main poles.

Even if no distortion exists, only the conductors under the pole faces generate voltage, and so the corrected average volts per bar should be

$$\frac{V \times p}{B \times \psi} \quad \text{volts}$$

where ψ is the ratio of pole arc to pole pitch, about 0.65. This is represented by D in Fig. 8-29. However, the maximum volts per bar at w is greater than this, as the height w is greater than D , or

$$\text{Maximum volts per bar} = \frac{V \times p}{B} \times \frac{w}{D \times \psi} \quad (8-13)$$

In practice, the value of w/D for a noncompensated machine at full-strength main field varies from about 1.7 to 1.9. However, any reduction in saturation causes the effects of the armature ampere-turns (which cause the distortion) to be magnified. The designer must check the actual value of w/D , since it may be as high as 4.5 for a dc motor at a weak main field strength (high speed). This is evident in Fig. 8-32. The distorting effect for the high-speed (low-average-flux) condition ϕ_{02} raises the maximum flux to ϕ_{w2} , which is over 3 times the change for the saturated

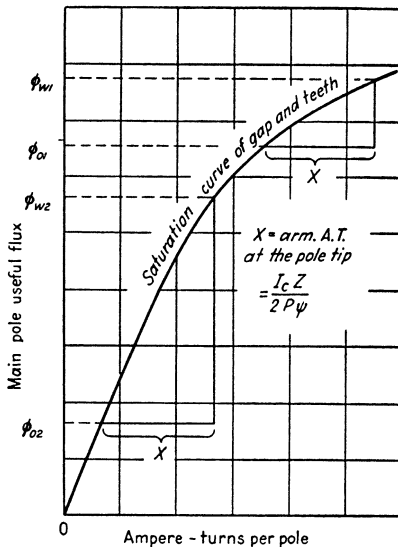


FIGURE 8-32 Effect of flux-distortion armature ampere-turns at normal and low saturation.

(low-speed) condition ϕ_{01} to ϕ_{w1} with the same distorting ampere-turns X .

The use of a compensating winding tends to eliminate the flux distortion, and for saturated conditions the flux curve coincides well with the no-load curve D of Fig. 8-29. However, under low saturation conditions the stationary compensating windings permit localized flux distortions. These are shown in Fig. 8-33. Similar distortions occur at low main flux densities on dc generators, but the output voltage V is reduced in the same proportion as the main flux, and the maximum voltage between bars is not affected seriously.

At full field on well-compensated motors or generators w/D is about 1.4 to 1.5. Direct-current motors at weak field may have ratios of 2.0 or more. On any questionable machine the designer should check this value carefully.

Approximate safe limits of maximum volts per bar are 40 V for motors and 30 V for generators on machines having 0.040-in-thick mica between segments.

Brush Potential Curves. When a dc machine develops some commutation sparking, the user may suspect

that the commutating-pole air gap is not set correctly. "Brush potential curves" are often taken to prove or disprove such suspicions.

These are taken by measuring the voltage drops between the brush and commutator surface at four points while the machine is operating at constant speed and load current (see Fig. 8-34). The voltages at 1, 2, 3, and 4 are taken by touching the pointed lead of a wooden pencil to the commutator surface. The circuit is completed with leads and a low-reading voltmeter is shown.

The voltages are then plotted. A curve such as A of Fig. 8-34 may indicate undercompensation due to a too large commutating-pole gap. Curve C may indicate overcompensation with too much flux density in the commutating-pole air gap. Curve B is typical of good compensation.

Justification for such conclusions is based on the theory that best commutation (coil current reversal) will be linear while the coil passes under the brush. This is possible only if there are no circulating currents. Undercompensation should cause circulating currents that would crowd the current to the leaving edge of the brush and cause a high voltage at point 4. Overcompensation would reverse the current too soon and would actually reverse the voltage drop at point 4.

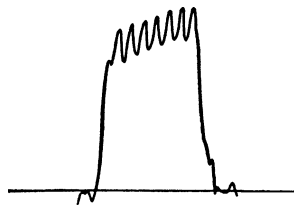


FIGURE 8-33 Main-pole flux distortion on a compensated motor at full load and $2\frac{1}{2}$ times base speed.

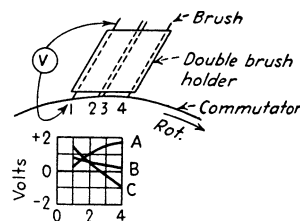


FIGURE 8-34 Brush potential curves.

Even to an expert, this test is only an indicator that more definitive tests, such as a buck-boost test, are needed [see Eq. (8-8)]. Many other factors, including brush riding, commutator surface conditions, and sparking, influence the readings. Where machine changes may be required, the manufacturer should be consulted.

8.6 ARMATURE DESIGN

EMF Equation. If 10^8 lines (Mx) of flux are cut by one conductor in 1 s, 1 V is induced in it. Therefore, the induced voltage of a dc machine is

$$E = \phi_t \times \frac{Z}{C} \times \frac{r/\text{min}}{60} \times 10^{-8} \quad (8-14)$$

where ϕ_t is the total flux in maxwells across the main air gaps and Z/C is the number of conductors in series per circuit (C).

Output Equation. Equation (8-14) is converted to watts output if both sides are multiplied by the load current I_L . $I_L \times C$. The formula can then be rearranged as

$$D^2 L = \frac{\text{watts} \times 6.08 \times 10^8}{r/\text{min} \times B_g \times \psi \times q} \quad (8-15)$$

where D is the armature diameter and L is the armature gross core length, B_g is the main-pole air-gap density in maxwells (lines), ψ is the ratio of pole arc to pole pitch, q is $ZI_c / \pi D$ (a useful loading factor), and ϕ_t is the total air-gap flux equal to

$$B_g \psi \pi D L \quad (8-16)$$

Rotor Speeds. Standards list dc generator speeds as high as are reasonable to reduce their size and cost. This relation is seen from Eq. (8-15). The speeds may be limited by commutation, maximum volts per bar, or the peripheral speeds of the rotor or commutator. Generator commutators seldom exceed 5000 ft/min, although motor commutators may exceed 7500 ft/min at high speeds. Generator rotors seldom exceed 9500 ft/min. Figure 8-35 shows typical standard speeds. If the prime mover requires lower speeds than these, generators can be designed for them but larger machines result.

Rotor Diameters. Difficult commutating generators benefit from the use of large rotor diameters, but diameters are limited by the same factors as rotor speeds listed above. The resultant armature length should be not less than 60% of the pole pitch, because such a small portion of the armature coil would be used to generate voltage. Typical generator diameters are shown in Fig. 8-36.

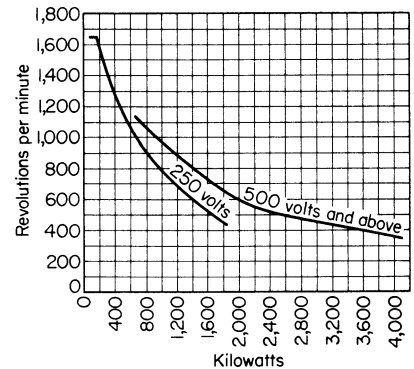


FIGURE 8-35 Standard speeds of dc generators.

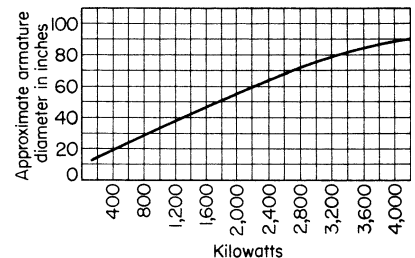


FIGURE 8-36 Approximate rotor diameters for standard speeds of dc generator.

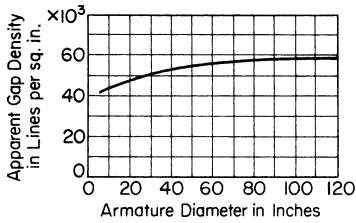


FIGURE 8-37 Curve of apparent gap density versus armature diameter.

Direct-current motor speeds must suit the application, and often the rotor diameter is selected to meet the inertia requirements of the application. Core lengths may be as long as the diameter. Such motors are usually force-ventilated.

Number of Poles and Other Rotor Design Factors.

The rotor diameter usually fixes the number of main poles. Typical pole pitches range from 17.5 to 20.5 in on medium and large machines. When a choice is possible, high-voltage generators use fewer poles to allow more voltage space on the commutator between

the brush arms. However, high-current generators need many poles to permit more current-carrying brush arms and shorter commutators. Commutators for 1000 to 1250 A/(brush arm) (polarity) are costly, and lower values should be used where existing dies will permit.

The main-pole air-gap flux density B_g is limited by the density at the bottom of the rotor teeth. The reduced taper in the teeth of large rotors permits the higher gap densities, as shown in Fig. 8-37.

Ampere conductors per inch of rotor circumference (q) is limited by rotor heating, commutation, and, at times, saturation of commutating poles. Approximate acceptable values of q are shown in Fig. 8-38.

The commutator diameter is usually about 55% to 85% of the rotor diameter, depending on the sizes available to the designer, the peripheral speed, and the resulting single clearances. Heating may also limit the choice.

Brushes and brush holders are chosen from designs available to limit the brush current density to 60 to 70 A/in² at full load, to obtain the needed single clearance, and to obtain acceptable commutator heating.

Selection of an Approximate Design. Consider a generator rated 2500 kW, 700 V, 3571 A, and 514 r/min. From Figs. 8-38 and 8-39

Approx. dia.	$D = 62$ in
Available dia.	$D = 56$ in
No. of poles	10
Pole pitch	17.59 in
Pole arc	12.0 in
(Arc/pitch)	0.687
Neutral zone	6.04 in
B_g gap density at 721 V	58,500 lines/in ²
Approx. q (Fig. 8-38)	1480 A cond./in
D^2L [Eq. (8-15)]	50,200 in ³
L (gross core)	16 in
No. of $\frac{3}{8}$ -in vents in core	5
Net core length	14.125 in
ϕ [Eq. (8-14)]	1.12×10^8
Approx. total cond. Z	752 (use 750)
Actual q	1520 A cond./in
No. of commutating bars (1-turn lap)	375
No. of slots	125
Slot pitch	1.407 in
Slot throw	$12\frac{1}{2}$ (use 12)
Chording	$\frac{1}{2}$ -slot pitches

Examination of the data indicates that the design appears feasible, and so we may continue.

Commutating dia.	39 in
Brush size (35°)	2(0.500 × 1.75) in
CZ (commutating zone) [Eq. (8-5)]	3.53 in
Brushes/arm	7b/a
Commutating speed	5250 ft/min
Commutating bar pitch	0.327
Brush arc	1.315 in
Bars/arc	4.02 bars
SC [Eq. (8-6)]	1.26 in
Brush density	58.3 A/in ²
Brush I^2R [Eq. (8-29)]	7142 W
Length of commutating face	7(1.75 + 0.063) + 1 = 14.56 in
Brush friction loss [Eq. (8-33)]	6760 W
Watts/in ² of commutating surface	7.8 W/in ²

Examination of these data also indicates that the proposed design is reasonable.

Armature Slots and Coils. The depth of an armature slot is limited by several factors, including the tooth density, eddy losses in the armature conductors, available core depths, and commutation. For reasonable frequencies (up to 50 Hz on medium and large dc machines), slots about 2 in deep can ordinarily be used.

Acceptable slot pitches range from 0.75 to 1.5 in. Small machines have shallower slots and a lower range of slot pitches. For medium and large machines, a reasonable tooth density usually results if the ratio of slot width to slot pitch is about 0.4.

Eddy losses in the conductors can be large compared with their load I^2R losses. Sometimes these must be reduced by making each armature conductor from several strands of insulated copper wire. The number of strands and their size depend on the frequency and the total depth of the conductor. An approximate formula for reasonable eddy losses is

$$\text{No. of strands} = (0.168)(f^{0.83})(d_c^{0.4}) \quad (8-17)$$

where f is the frequency in hertz, $(\text{r/min} \times \text{poles})/120$, and d_c is the total depth of a conductor.

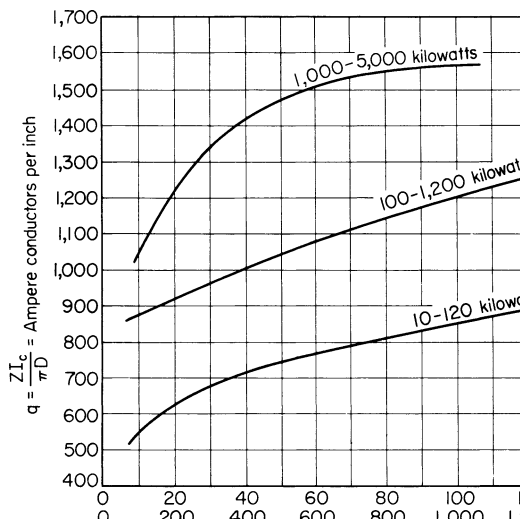


FIGURE 8-38 Ampere conductors per inch of armature - circumference.

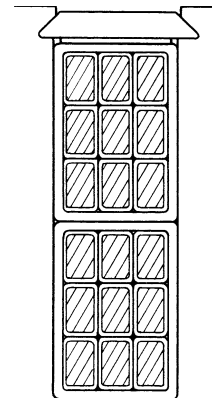


FIGURE 8-39 Armature slot cross section.

The insulation space required depends on the type used. Typical conductor strands have about 0.018 in of glass strands and varnish total. Mica wrappers, binding tapes, and varnish and slot finish allowance (0.010 in) total about 0.085 in on the coil width. If the space for the wedge and its retainer is included, the two coils depthwise total about 0.315 in (see Fig. 8-39).

Approximate Slot Design

Width [see text preceding and following Eq. (8-17)] 0.4×1.407	0.563 in
Depth	2.0 in
Approx. total cond. depth	0.875 in
Frequency	42.8 Hz
No. of strands/conductor [Eq. (8-17)]	3
	Slot width, in
	Depth, in
Approx.	
Size	0.563 in
Insulation	0.139 (0.085 + 0.054)
Bare copper	0.424 in
Strand size	0.141 in
Use	3 (0.144)
Use available slot	0.570 in
	2.000 in
	0.423 (0.315 + 0.108)
	1.577 in
	0.263 in
	0.289 in strands/conductor
	2.250 in

8.7 COMPENSATING AND COMMUTATING FIELDS

Compensating Winding Data. The compensating winding should closely match the armature ampere-turns per inch, should avoid causing magnetic noise, and should result in an acceptable maximum volts per bar. Machines for 40°C temperature rise will have compensating bar densities of about 2500 to 3000 A/in². The pole tip section will limit the maximum depth of the compensating bar. Localized areas of high flux density must be avoided where flux must funnel between the pole “shoe” surface and the bottom of the compensating slot.

For single compensating bar-per-slot designs, the typical width required for insulation, varnish, and stacking factor is about 0.140 in. With the wedge space included, the insulation-depth requirement is about 0.400 in.

Compensating Winding Calculations

q (armature)	1520 A cond./in
Pole arc of 12.1 in covers	18,400 A cond.
Approx. compensating At	9200 At
Load current	3571 A
Approx. turns/pole 2.68	Use 2.5 turns/pole
Consider 5 slots/pole	1 bar/slot = 2.5 turns/pole
Size of compensating bar	0.688×2.0 in
Bar density	2590 A/in ²
Compensating slot width 0.828	Use 0.830 in
Compensating slot depth 2.400	Use 2.400 in
Compensating slot pitch (layout)	2.25 in
Rotor slot pitch	1.407 in
No magnetic noise	Improbable
Maximum volts/bar	See last two paragraphs in Sec. 8.8.

Commutating Winding Calculations. The total of the commutating and compensating ampere-turns per pole should be about 120% to 130% of those on the rotor.

Armature At/pole = $ZI_c/2p = (750 \times 357)/(2 \times 10)$	13,400 At/pole
Equiv. armature-turns/pole on line ampere basis	3.75 turns/pole
Approx. commutating + compensating At/pole ($1.2 \times 13,400$)	16,100 At/pole
Commutating + compensating turns/pole $16,100/3571$	4.5 turns/pole
Less compensating turns/pole	-2.5 turns/pole
Requires commutating winding of	2.0 turns/pole
Excess At/pole, $16,100 - 13,400$	2700 At/pole

Well-ventilated commutating coils may have densities of 2000 to 2500 A/in² (see Fig. 8-48).

Commutation Calculations

E_c = reactance voltage of commutation	5.42 V [see Eq. 8-4]
Commutating-pole gap density B_m	13,550 L/in ² [Eq. (8-7)]
Excess At	2700 At/pole
Commutating-pole air gap	0.609 in [Eq. (8-8)]

8.8 MAGNETIC CALCULATIONS

Flux Paths. Figure 8-40 shows the paths of the main-pole flux for a typical medium-sized machine. The commutating poles and the compensating slots are not shown. Saturation calculations involve only half the length of a complete flux loop, because that is all that one field coil accommodates. Except for the main-pole air gap and the rotor teeth ampere-turns, the calculations are simple. They require (1) the determination of flux densities by dividing the flux in a section by its cross-sectional area, $\beta = \Phi/\text{area}$; (2) reading a magnetization curve for the material involved to find the ampere-turns per inch needed for the density; and (3) finding the total ampere-turns for the part by multiplying the length of the portion of the path by those ampere-turns per inch. Typical magnetization curves are shown in Fig. 8-41.

The rotor core is usually built up of sheet steel laminations 0.017 to 0.025 in thick. Because of burrs and surface coatings, a stacking factor of 93% is common. The main poles use thicker laminations, and a factor of 95% is common. If the frame is also made up of laminations, a similar factor is necessary. Of course, a solid frame uses its full area.

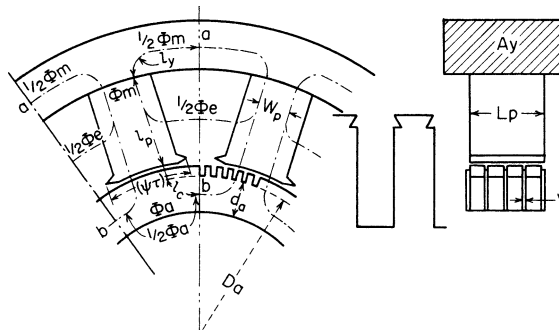


FIGURE 8-40 Paths of main and leakage fluxes.

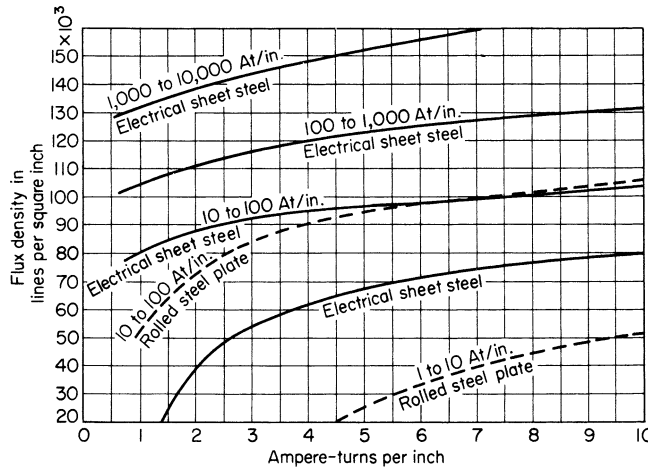


FIGURE 8-41 Magnetization curves.

The leakage flux ($1/2 \phi_e$) in Fig. 8-40 from the main field coils must be included with the useful flux in the frame yoke and the pole body. Calculations depend on the actual machine dimensions and on the main field ampere-turns. However, the ampere-turns in these parts represent only a small part of the total required for the entire path, and it is usually accurate enough to estimate this leakage to be 12% of the useful flux normally and 20% at high saturations. For accurate calculations, the actual leakage can be plotted. No leakage fluxes are considered in computing the gap, teeth, or core densities.

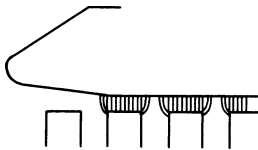


FIGURE 8-42 Distribution of flux in the air gap.

The Carter Coefficient and Gap Ampere-Turns. The presence of rotor slots, compensating slots, and vent ducts in the generator causes the actual densities in the main-pole air gap to be greater than for a smooth, solid core. Also, the average lengths of the flux paths are longer (see Fig. 8-42). The two effects may be lumped by assuming that the air gap is larger than measured mechanically. On considering the three factors (rotor slots, compensating slots, and vents) in succession, the formula

$$G_1 = G \times \frac{G + (\text{slot width}/5)}{G + (\text{slot width}/5)(1 - \text{slot width}/\text{slot pitch})} \quad (8-18)$$

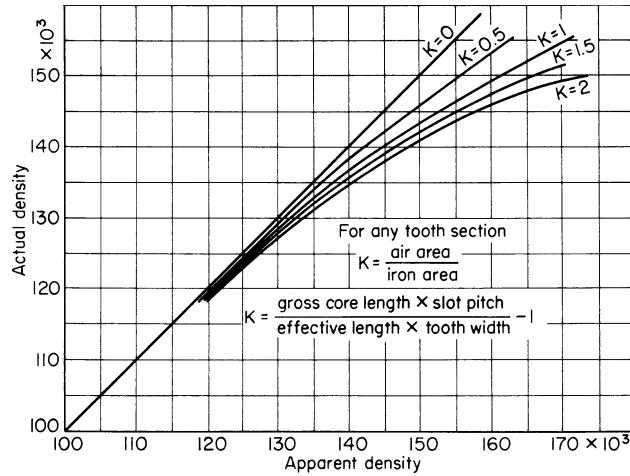
gives the first corrected air gap G_1 ; this will closely approximate the effective air gap.

The ampere-turns across the gap will be

$$At_g = \beta_g \times 0.313 \times G_1 \quad (8-19)$$

The Rotor Teeth Ampere-Turns. For tooth densities below 100,000 lines/in², the ampere-turn drops in a tooth are so low that practically no flux will pass down the adjacent slot because the reluctance of air is so great. However, as tooth flux densities become larger, they produce very high ampere-turn drops from the top of the tooth to its bottom owing to saturation. Because these ampere-turns are also across the parallel flux path in the adjacent slot, when they are large enough, some useful flux will pass down the slot, relieve the tooth of some of its flux, and lower its actual density. If the tooth apparent density is calculated by assuming that all the flux across a slot pitch passes down the tooth, the actual density will be less than the apparent, depending on the amount of saturation.

The relation between the apparent tooth density β_a and the actual tooth density β_t for different ratios of air area to iron area at any section of the tooth is shown in Fig 8-43. The K of these areas is

FIGURE 8-43 K curves.

$$K = \frac{\text{air area}}{\text{iron area}} = \frac{(\text{gross core length}) \times (\text{slot pitch})}{(\text{eff. core length}) \times (\text{tooth width})} - 1 \quad (8-20)$$

For accuracy in calculating tooth ampere-turns, it is desirable to divide the tooth into several parts, find the ampere-turns drop across each section, and total them. The flux density is found at the middle of each section, and the K ratio is calculated at the middle of each section.

Calculation of No-Load Saturation Data. Considering the 2500-kW, 700-V, 3571-A, 514-r/min generator, we have the values shown in Table 8-1. Using the magnetization curves of Fig. 8-41 and these data, the no-load saturation curve is calculated for several voltages. Note that 721 V is chosen in Table 8-2 on the assumption that the IR drop in the generator will not exceed 3%, or 21 V in this case. The generator (Fig. 8-44) must have this additional voltage induced in it for a 700-V terminal voltage. In the case of a motor, the induced voltage would be lower by the amount of the IR drop, or 679 V.

Full-Load Saturation Curve for a Compensated Machine. Figure 8-45 shows the calculated no-load saturation curve. For a well-compensated machine, the brushes will have little or no shift, and essentially no useful flux will be lost because of armature reaction. Only the armature-circuit-resistance IR drop need be considered, and the full-load excitation ampere-turns required can be read directly from the no-load saturation curve at the induced voltage.

For the 2500-kW generator, the excitation required at 721 V is 7520 At at full load.

TABLE 8-1 Magnetic Dimensions

Section	K	Net area, in ²	Eff. length, in
Frame yoke 6×17	—	102	13.85
Pole body $9 \frac{1}{2} \times 15 \frac{1}{2}$	—	140	10.35
Compensating pole teeth (layout)	—	100	2.40
Effective air gap	—	—	0.268
Tooth 1 (upper $\frac{1}{3}$)	0.92	10.8	0.75
Tooth 2 (middle $\frac{1}{3}$)	0.96	10.3	0.75
Tooth 3 (bottom $\frac{1}{3}$)	1.00	9.8	0.75
Core	—	79.3	7.15

Note: 1 in = 25.4 mm; 1 in² = 645 mm².

TABLE 8-2 Calculated Ampere-Turns per Pole

Volts	ϕ_t	Gap, $L = 0.268$		Tooth 1, $L = 0.75,$ $K = 0.92$		Tooth 2, $L = 0.75,$ $K = 2.96$		Tooth 3, $L = 0.75,$ $K = 1.0$		Core, $L = 7.15$		Frame, $L = 13.85$		Pole, $L = 10.35$		C. tooth, $L = 2.40$		Total ampereturns
		β	At	Apparent β Actual β At/in	At	Apparent β Actual β At/in	At	Apparent β Actual β At/in	At	β At/in	At	β At/in	At	β At/in	At	β At/in	At	
420	65.5×10^6	33,800		70,500 70,500 5.4	74,600 74,600 7.2	78,000 78,000 9.0		81,000 81,000 9.0		2.1 15	6.5 90	36,000 36,000		2.8 30	52,400	65,500		3,018
630	98.3×10^6	50,800		106,000 106,000 130	112,000 111,300 210	117,000 116,200 320		122,000 121,200 160		62,000 3.7	54,000 11	54,000 11		78,600 9.2	78,600	98,300		5,065
721	112.5×10^6	58,200		120,500 120,500 440	126,500 126,500 660	132,300 132,300 1,000		138,000 137,000 750		71,000 5.7	61,800 14	61,800 14		90,000 26	90,000	112,500		7,520
770	120×10^6	62,100		128,000 128,000 710	134,600 134,600 1,200	139,000 139,000 1,850		144,000 143,000 2,100		75,800 7.9	66,000 16	66,000 16		96,000 46	96,000	120,000		9,790

Note: L = length of flux path, in; K = air area/iron area at particular position on tooth; apparent β = apparent flux density, lines/in²; actual β = actual flux density, lines/in²; At/in = ampere-turns per in; At = ampere-turns (1 in = 25.4 mm; 1 in² = 645 mm²).

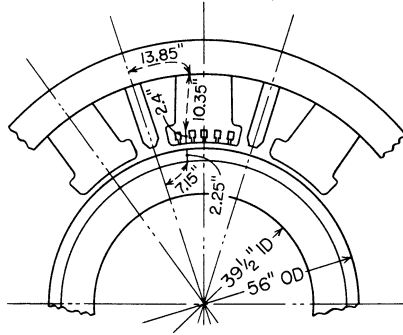


FIGURE 8-44 Cross section of a 2400-kW generator.

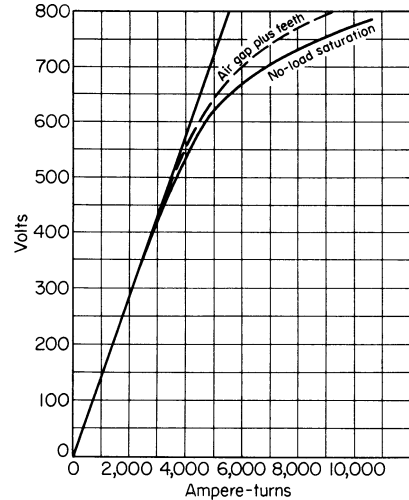


FIGURE 8-45 No-load saturation curves.

Full-Load Saturation Curve for a Noncompensated Machine. With commutating poles, there is no need for brush shift, but the uncompensated armature reaction will result in loss of useful flux as the load is increased. Figure 8-46 shows a method of calculating the additional ampere-turns excitation to replace this lost flux.

OBD = saturation curve of air gap plus teeth and pole face

BC = *IR* drop in armature circuit plus the brush drop. *B* = any point chosen on curve *OBD*

FB = *BE* = full-load-armature *At*/pole arc, or $At/p \times \psi$, laid off on a horizontal line

Through *E* and *F*, draw vertical lines of indefinite length. Move line *GI* vertically upward or downward parallel to *FBE* to a position *GHKI*, so that area *JGHOJ* area *HABDIKH*.

Through *B* draw a vertical line *BCK*. Then *HK* distortion ampere-turns for the load-current considered for point *B*.

Through *C*, draw a horizontal line of indefinite length cutting the no-load saturation curve at *A*.

CP = *HK*, to be extended from right at *C*

AP = total ampere-turns required at load current considered to maintain load at same value as at no load

By choosing several points, such as *B*, along the saturation curve and making the same calculations for each point, a full-load or any load saturation curve can be produced.

Maximum Volts per Bar Calculations. The distorting ampere-turns resulting from imperfect compensation of the armature ampere-turns by the compensating winding are found by plotting the two and noting the maximum difference. This is done at the maximum-overload-current point.

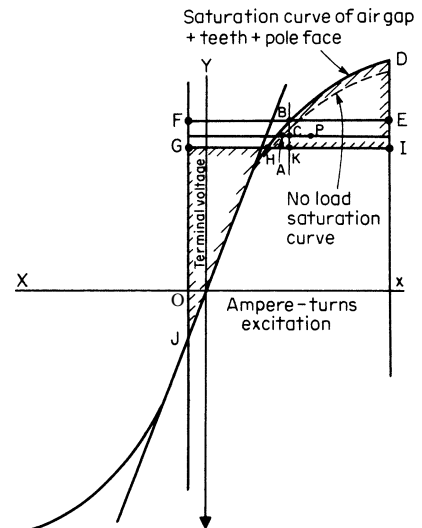


FIGURE 8-46 Calculation of load saturation curve.

The distortion factor (Figs. 8-32 and 8-45) is determined from the gap and teeth saturation curve (Fig. 8-45). At double load, the induced voltage is considered to be 740 V.

Volts between arms	700 V
No. of poles p	10
No. of commutating bars	375
Pole arc/pole pitch ψ	0.687
Distorting ampere-turns	1600 At
Distortion factor w/D of Fig. 8-32	1.06
Max. V/bar	$[(V \times p)/B] \times [w/(D \times \psi)]$ [Eq. (8-13)]
Max. V/bar	28.8 V/bar

This value is acceptable.

8.9 MAIN FIELDS

Main Field and Main-Field Heating. Figures 8-47 and 8-48 show three types of dc main fields. Small machines commonly use those of Fig. 8-47. They are wound on molds and then slipped on the poles. Type A is wound on an insulating spool, and type B uses an insulated steel spool for better heat transfer and mechanical protection.

The arrangement of Fig. 8-48 is common on large and medium-sized dc machines. The turns of the inner section are wound tightly on the insulated pole body to avoid air spaces between the pole and the coil. This permits maximum heat transfer. The second section is spaced away from the inner coil to permit the cooling air to flow over the maximum surface area possible. The thickness of a coil section is limited to about $1\frac{1}{4}$ to $1\frac{3}{4}$ in for a small temperature gradient within the coil.

All three types may use wire insulated with varnish, double cotton covering, or glass slivers in varnish. Air pockets which act as barriers to transfer of heat must be avoided, and so rectangular wire is common. Also, varnish or resin is liberally applied during winding or applied by vacuum impregnation after the coil is wound.

Design criteria suitable for all dc machines cannot be established, because the field cooling depends on air pressures from the armature rotation, the air-passage areas through the fields, and the radiation of heat from adjacent parts. These factors vary with machine design. However, on medium and large self-ventilated dc generators (built as in Fig. 8-48) empirical data are useful.

The main fields receive heat, not only from their own I^2R losses, but from heat radiated from the hot armature and the commutation coils. Also, the air cooling the coils is already heated by the

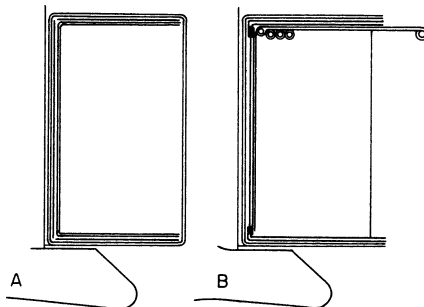


FIGURE 8-47 Two types of field-coil insulation, combined with fiber and metal spools, respectively.

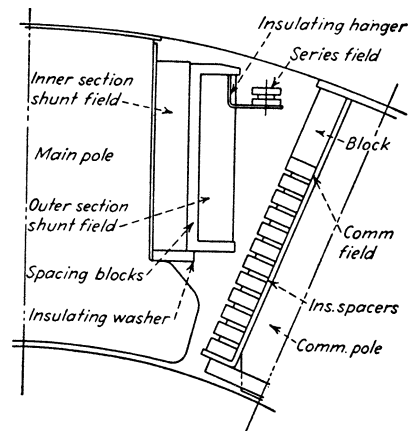


FIGURE 8-48 Ventilated field coils.

rotor. This lowers the temperature gradient for cooling the coils. The temperature rise of the fields must be calculated, not on the basis of the actual air temperature, but on the basis of the cool ambient-air temperature outside the machine. Figure 8-49 shows empirical data for such typical self-ventilated medium and large machines, built as shown in Fig. 8-48.

The "surface area" for these curves includes the entire periphery of the coil, because the heat transfer to the pole body is as effective as that to the air-cooled surfaces.

Little gain is made in cooling with increase in rotor velocities above 5000 ft/min because most of the armature air must pass through the limited field structure area. At high rotor speeds, the air is throttled owing to the high-velocity pressure drops.

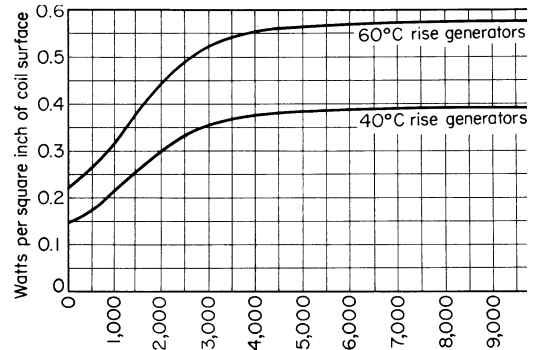


FIGURE 8-49 Main-field loss per surface area.

Main-Field Calculations. These are made by making a layout similar to that shown in Fig. 8-48. This permits the estimate of approximate mean length of turns ($\bar{L}_t$) for the sections.

The means of excitation and the particular application usually determine the IR drop of the main field. This is met in design by selection of the field wire cross-sectional area. This is calculated by Eq. (8-21).

$$\text{Conductor sectional area} = \frac{At/p \times \bar{L}_t \times p \times 8.25 \times 10^{-7}}{IR} \quad (8-21)$$

where At/p is the number of ampere-turns per pole needed, $\bar{L}_t$ is the mean length of turns, p is the number of coils in series, and IR is the required voltage drop.

Typical field calculations are

At/p	7520 At
Approx. $\bar{L}_t$	55 in
IR drop needed	90V
Conductor area [Eq. (8-21)]	0.038
Insulation conductor	0.018 in
Section of coil	6.78 × 1.6 in
Actual IR	86.5 V
Watts ($IR \times I$)	3380 W
W/in ²	0.362 W/in ²
W/in ² allowed	0.388 W/in ²
Res. 75°C	2.21Ω
Coils in series	10
Copper	0.162 × 0.258 = 0.04 in ²
Coil	24T high × 8lay. 192T/coil
Layout $\bar{L}_t$	55.65 in
$I = At/t$	39.1 A
Surface $2H + tk(\bar{L}_t)p$	9350 in ²
Rotor velocity	7350 ft/min
Current density	977 A/in ²

These data indicate an acceptable field.

8.10 COOLING AND VENTILATION

Cause of Temperature Rise. The losses in a dc machine cause the temperature of the parts to rise until the difference in temperature between their surfaces and the cooling air is great enough to dissipate the heat generated.

Permissible measured temperature rises of the parts are limited by the maximum “hot-spot” temperature that the insulation can withstand and still have reasonable life. The maximum surface temperatures are fixed by the temperature gradient through the insulation from the hot spot to the surface.

The IEEE Insulation Standards have established the limiting hot-spot temperatures for systems of insulation. The *American National Standards Institute* Standard C50.4 for dc machines gives typical gradients for those systems, listing acceptable surface and average copper temperature rises above specified ambient-air temperatures for various machine enclosures and duty cycles. Typical values are 40°C for Class A systems, 60°C for Class B, and 80°C rise for Class F systems on armature coils. Class H systems usually contain silicones and are seldom used on medium and large dc machines. Silicone vapors can cause greatly accelerated brush wear at the commutator and severe sparking, particularly on enclosed machines.

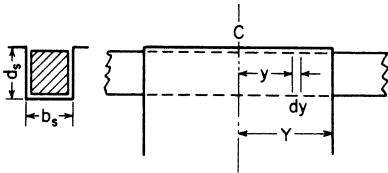


FIGURE 8-50 Heat paths in an armature conductor.

Temperature Gradients in Rotor Coils. Figure 8-50 represents a current-carrying conductor insulated from the core slot in which it is embedded. The hot spot is probably at the core centerline and near the center of the conductor. Heat will probably travel along the conductor to the end turn and also through the insulation to the iron. The amount of heat flowing in each direction is difficult to calculate. Also, variations in the coils, such as resin fill and tightness in the slots, make heat conductivity factors difficult to predict.

1. Assume that all the heat must travel down the conductor to the end turn. What will be the temperature difference in the conductor between the center of the core and its edge?

$$\text{Resistivity of copper at } 75^{\circ}\text{C} = 8.25 \times 10^{-7} \Omega/\text{in}^3$$

$$\text{Thermal cond. copper} = 9.75 \text{ W}/(\text{in})(^{\circ}\text{C}) \text{ for } 1\text{-in}^2 \text{ section}$$

Therefore, the energy crossing dy of Fig. 8-50 is

$$\text{Watts} = (I_c)^2 R_y = \frac{(I_c)^2 (y)(8.25 \times 10^{-7})}{A} \quad (8-22)$$

where I_c is the conductor amperes, R_y the resistance of length y , and A the conductor cross-sectional area. The difference in temperature between two faces dy apart is

$$^{\circ}\text{C} = \frac{(I_c)^2 (y)(8.25 \times 10^{-7})}{A} \times \frac{dy}{A} \times \frac{1}{9.75} \quad (8-23)$$

and the difference in temperature between the center C and any point y is

$$^{\circ}\text{C} = \frac{(I_c)^2 (8.25 \times 10^{-7})}{A} \int_0^y \frac{y dy}{A} \times \frac{1}{9.75} \quad (8-24)$$

or

$$^{\circ}\text{C} = 4.22 \left(\frac{I_c}{A} \right)^2 (y)^2 (10)^{-8}$$

Consider a current density of 2920 A/in² and a total core length of 16 in. Then the coil temperature gradient from the core center, with no ventilating ducts, to the edge is 28.8°C. This assumes that no heat passes through the insulation to the iron, and so medium and large machines normally use ventilating core ducts every few inches.

2. Assume that the end turns are so hot that no heat flows longitudinally down the coil. The I^2R loss of each inch of conductor length is

$$\text{Watts} = \frac{(I_c)^2(8.25 \times 10^{-7})}{A}$$

If the slot contains several conductors

$$\text{Watts} = (\text{ampere conductors})(A/\text{in}^2)(8.25 \times 10^{-7})$$

and the temperature difference between the bare conductor and the steel across the insulation is

$$^{\circ}\text{C} = (\text{amp conductors})(A/\text{in}^2) \times \frac{\text{insulation thickness}}{2d_s + b_s} \times \frac{8.25 \times 10^{-7}}{0.003} \quad (8-25)$$

The factor 0.003 is the thermal conductivity of the insulation in watts per cubic inch per degree Celsius W/(in³)(°C) difference. Thus, for 2142 ampere conductors per slot, 2920 A/in², a surface of two slot depths plus a slot width (times 1 in) = 5.07 in², and an insulation thickness of 0.051 in the temperature drop across the insulation is 17.65°C.

This figure cannot be considered precise because the thermal conductivity can vary widely with the insulation used and the presence of varying amounts of air in it. The conductivity figure for air is 0.0007, whereas that of mica is 0.007 W/(in³)(°C). Also, heat moves along the coil. Because of these difficulties, empirical data from actual machines are more reliable and easier to use.

Heating of End Connections of Armature Windings. Small machines often have “solid” end windings banded down on insulated “shelf”-type coil supports. Larger machines are more heavily loaded per unit volume and usually have narrow coil supports, air spaces between the end turns, and ventilating air scouring both the top and bottom surfaces of the coil extensions.

With this construction, the approximate allowable product of ampere conductors per inch of outer circumference times the amperes per square inch for various rotor velocities is shown in Fig. 8-51 for a 40°C rise on the end turns.

Commutator Heating. A modern dc armature is shown in Fig. 8-52. The commutator diameter ranges from 55% to 85% of the rotor core, and the commutator necks joining the bars with the rotor

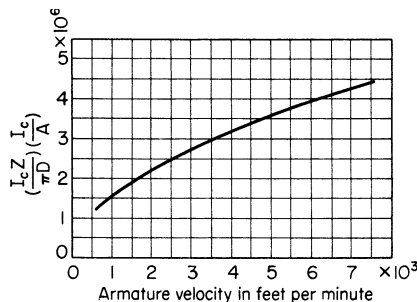


FIGURE 8-51 End-winding cooling.

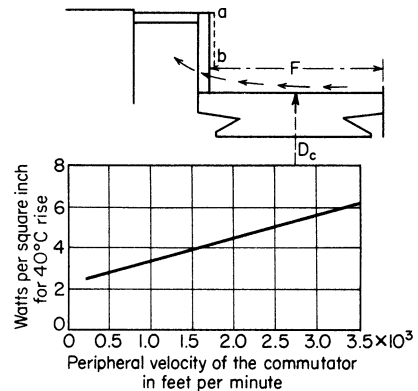


FIGURE 8-52 Temperature rise of a commutator.

winding extensions are usually separated from one another by air spaces, so that, when the armature revolves, air circulation is set up as shown by the arrows.

A typical relation between permissible watts per square inch of commutator surface and its peripheral velocity is shown in Fig. 8-52. The radiating surface is the commutator circumference times its face length. Neck area is not included.

The heat to be dissipated is that due to brush friction and the brush contact I^2R losses. There may be other losses due to poor commutation, brush chattering, and commutator surface, and, if so, the rise will be greater than indicated in Fig. 8-52. If commutation is very good and brush riding excellent, the temperature will be lower.

Application of Heating Constants. The paragraphs covering the design of the armature, main fields, compensating windings, and commutating windings included typical loading data such as ampere conductors per inch, amperes per square inch, flux densities, and watts per square inch of cooling surface. More accurate data depend on the exact arrangements used in a particular design. If possible, new design should be compared with similar machines which have already been tested. Any machine enclosure variation that restricts or increases the ventilation will affect the temperature rises.

8.11 LOSSES AND EFFICIENCY

Armature Copper I^2R Loss. At 75°C the resistivity of copper is $8.25 \times 10^{-7} \Omega/\text{in}^3$. Thus, for an armature winding of Z conductors, each with a length of $\bar{L}_t/2$ (half the mean length turn of the coil), each with a cross-sectional area of A and arranged in several parallel circuits, the resistance is

$$R_a = Z \frac{\bar{L}_t}{2A} \frac{8.25 \times 10^{-7}}{(\text{circuits})^2} \quad \text{ohms} \quad (8-26)$$

The $\bar{L}_t$ is best found by layout, but an approximate value is

$$\bar{L}_t = 2[(1.35)(\text{pole pitch}) + (\text{rotor length}) \times 3] \quad (8-27)$$

There are also eddy current losses in the rotor coils, but these may be held to a minimum by conductor stranding in accordance with Eq. (8-17). Some allowance for these is included in the load loss.

Compensating, Commutating, and Series Field I^2R Losses. These fields also carry the line current, and the I^2R losses are easily found when the resistance of the coils is known. Their $\bar{L}_t$ is found from sketch layouts. At 75°C

$$R = T \frac{\bar{L}_t}{A} \frac{8.25 \times 10^{-7}}{(\text{circuits})^2} p \quad \text{ohms} \quad (8-28)$$

where R is the field resistance in ohms, T the number of turns per coil, p the number of poles, $\bar{L}_t$ the mean length of turn, and A the area of the conductor. The total of these losses ranges from 60% to 100% of the armature I^2R for compensated machines and is less than 50% for noncompensated machines.

The brush I^2R loss is caused by the load current passing through the contact voltage drop between the brushes and the commutator. The contact drop is assumed to be 1 V.

$$\text{Brush } I^2R \text{ loss} = 2(\text{line amperes}) \quad \text{watts} \quad (8-29)$$

Load Loss. The presence of load current in the armature conductors results in flux distortions around the slots, in the air gap, and at the pole faces. These cause losses in the conductors and iron that are difficult to calculate and measure. A standard value has been set at 1% of the machine output.

$$\text{Load loss} = 0.01(\text{machine output}) \quad (8-30)$$

Shunt Field Loss. Heating calculations are concerned only with the field copper I^2R loss. It is customary, however, to charge the machine with any rheostat losses in determining efficiency. Thus

$$\text{Shunt field and rheostat loss} = I_f V_{ex} \quad \text{watts} \quad (8-31)$$

where I_f is the total field current and V_{ex} is the excitation voltage.

Core Loss. As seen from Fig. 8-53, the flux in any portion of the armature passes through $p/2$ c/r (cycles per revolution) or through $(p/2)[(\text{r/min})/60]$ Hz.

The iron losses consist of the *hysteresis loss*, which equals $K\beta^{1.6}fw$ watts, and the *eddy current loss*, which equals $K_e(\beta ft)^2w$ watts. K is the hysteresis constant of the iron used, K_e is a constant inversely proportional to the electrical resistance of the iron, β is the maximum flux density in lines per square inch, f is the frequency in hertz, w is the weight in pounds, and t is the thickness of the core laminations in inches.

The eddy loss is reduced by using iron with as high an electrical resistance as is feasible. Very high resistance iron has a tendency to have low flux permeability and to be mechanically brittle and expensive. It is seldom justified in dc machines. The loss is kept to an acceptable value by the use of thin core laminations, 0.017 to 0.025 in thickness.

Another significant loss is the *pole-face loss*. Figure 8-42 shows the distribution of flux in the air gap of a dc machine. As the armature rotates and the teeth move past the pole face, emfs are induced which tend to cause currents to flow across the pole face. These losses are included in the core loss.

Unfortunately, there are other losses in the core that may differ widely even on duplicate machines and that do not lend themselves to calculation. These include:

1. Loss due to filing of slots. When the laminations have been assembled, it will be found in some cases that the slots are rough and must be filed to avoid cutting the coil insulation. This burrs the laminations and tends to short circuit the interlaminar resistance.
2. Losses in the solid spider, core end plates, and coil supports from leakage fluxes may be appreciable.
3. Losses due to nonuniform distribution of flux in the rotor core are difficult to anticipate. In calculating core density, it is customary to assume uniform distribution over the core section. However, flux takes the path of least resistance and crowds behind the teeth until saturation forces it into the less used, longer paths below. As a result of the concentration, the core loss, which is about proportional to the square of the density, is greater than calculated.

Thus, it is not possible to predetermine the total core loss by the use of fundamental formulas. Consequently, core-loss calculations for new designs are usually based on the results from tests on similar machines built under the same conditions. Such test results are plotted in Fig. 8-54 for

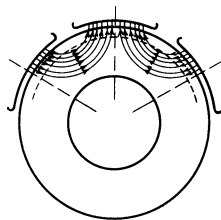


FIGURE 8-53 Distribution of flux in the armature.

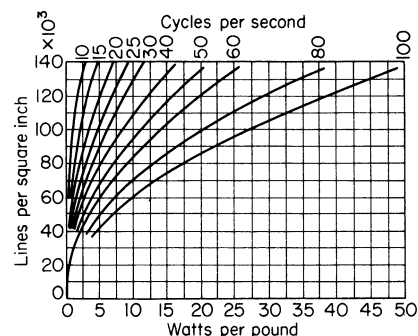


FIGURE 8-54 Iron-loss curves for a dc machine.

machines using ordinary laminations 0.017 in thick and a limited amount of filing. They do not include the pole-face losses, which would increase the values about 30%.

Brush Friction Loss. This loss varies with the condition of the commutator surface and the grade of carbon brush used. A typical machine has about 8-W loss/(in² of brush contact surface) (1000 ft/min) of peripheral speed when normal brush pressure of 2½ lb/in² is used.

$$\text{Brush friction} = (8) (\text{contact area}) \frac{\text{peripheral velocity}}{1000} \quad (8-32)$$

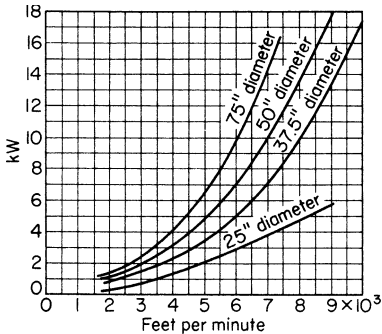


FIGURE 8-55 Friction and windage versus rotor velocity.

Friction and Windage. Most large dc machines use babbit bearings and many small machines use ball or roller bearings, although both types of bearing may be used in machines of any size. The bearing friction losses depend on the speed, the bearing load, and the lubrication. The windage losses depend on the construction of the rotor, its peripheral velocity, and the machine restrictions to air movement. The two losses are lumped in most estimates because it is not practical to separate them during machine testing.

Figure 8-55 shows typical values of friction and windage losses for various rotor diameters referred to rotor velocities.

Efficiency. The efficiency of a generator is the ratio of the output to its input. The prime mover must supply the output and, in addition, the sum of all the losses. This is the input

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}} \quad (8-33)$$

8.12 GENERATOR CHARACTERISTICS

The voltage regulation of a dc generator is the ratio of the difference between the voltage at no load and that at full load to the rated-load voltage. The characteristic is normally drooping as the load is increased, but it can rise because of series field effects or the action of circulating currents of communication at very low voltage operation.

For a dc generator, the terminal-voltage equation is

$$TV = E - IR = [K\phi_r](r/\text{min}) - IR \quad (8-34)$$

where E is the induced emf, IR is the armature circuit drop, K is a constant depending on the machine design, and ϕ_r is the total main-pole flux of the generator.

The regulation curves are easily calculated by using the no-load and full-load saturation curves shown in Fig. 8-56. The effect of the excitation method is found by the use of the field and rheostat IR line for self-excited machines and by the constant-ampere-turn line for separate excitation.

A separately excited compensated generator which is shunt-wound will have a voltage-load characteristic which will approach a straight line; it droops to full load an amount equal to the percent IR drop. There is little or no flux loss due to armature reaction or brush shift.

At voltages 10% or less of rated, the main-field strength is so weak that currents circulating in the coils short-circuited by the brushes at commutation may cause an increase in main-pole flux with load that causes a rising characteristic. These armature coils loop the main poles and their ampere-turns produce direct axis flux. A rising voltage characteristic can be undesirable, particularly if the generator supplies a dc motor whose speed is caused to rise with load, since this causes instability.

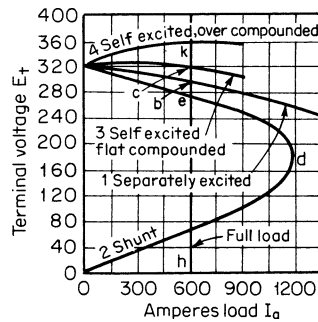


FIGURE 8-56 External characteristics versus excitation methods.

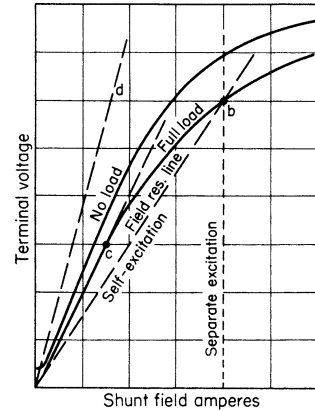


FIGURE 8-57 No-load and field-load saturation curves.

A separately excited noncompensated dc generator which is shunt-wound has a nonlinear loss of flux due to armature reaction as the load current is increased. It can be seen from Eq. (8-35) that this causes a characteristic which droops at an ever-increasing rate with load increase, giving a curve which is concave downward.

A self-excited noncompensated dc generator which is shunt-wound has its shunt-field excitation decreased as the terminal voltage drops. This results in a reduction of main-field ampere-turns and a loss of still more flux. This gives a severe droop which may be so great that, above a certain peak-load current, the terminal voltage will not be high enough to provide enough field current to maintain the voltage and load current and the voltage will collapse, as shown in *d* of Fig. 8-57.

Instability of Self-Excited Generators. A self-excited dc generator is unstable if the rheostat line does not make a definite intersection with the load-saturation curve (see Fig. 8-56). The shunt-field current is fixed by the terminal voltage, and the resistance is in the shunt-field circuit. Instability will exist if the slope of the rheostat line is nearly equal to or greater than the slope of a line tangent to the operating point on the saturation curve. In Fig. 8-57, point *b* is a stable operating condition, but point *c* is not, because a decrease in voltage decreases the shunt field ampereturns, and this produces a further decrease in voltage.

If the field circuit resistance were set at *d*, the self-excited generator would never build up beyond residual voltage. Another cause of failure to build up may be the connection of the shunt field. If the current flow due to residual voltage is such that it tends to kill the flux producing the residual voltage, no buildup occurs.

Compound-Wound DC Generators. The generators described above can be compounded by adding series fields excited by the load current. However, the resulting field strength of these fields is linear with load and the shape of the voltage-regulation curve is not changed thereby but is merely rotated upward or downward with the zero-load point as a pivot.

Series Generators. Curve 1 of Fig. 8-58 shows the relation between voltage and current if there is no armature resistance or armature reaction. This is actually the no-load curve of the machine obtained by separately exciting the series field. Curve 2 shows the

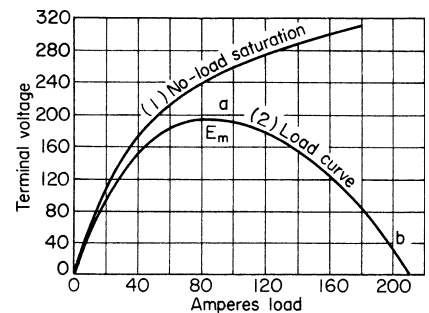


FIGURE 8-58 Characteristic curves of a series generator.

actual relation between load current and terminal voltage. The total voltage drop is made up of a part caused by the decrease in flux by armature reaction and a part caused by the IR drop of the armature, brushes, and series fields.

Field Time Constants. The major delay in change of output voltage by an excitation change is caused by the inductance of the main fields. The time constant of the shunt field is the ratio of its inductance in henries to its resistance in ohms, and this ratio represents the time in seconds required for 63% of a field current change to occur when the excitation voltage is suddenly changed. In the case of the 2500-kW generator, a mean main-field inductance over the voltage range from zero to rated is 6.20 H. The main-field resistance is 2.21Ω . The field time constant is therefore 2.8 s.

The inductance L of a coil is the incremental change of flux linkages per incremental change in field current times 10^8 . This is proportional to the slope of the saturation curve and is constant over the air-gap line. It is therefore a decreasing variable after the curve leaves the air-gap line (see Fig. 8-45). The overall inductance, as the voltage builds up from zero, is not so high as that of the air-gap portion or as low as at the rated-voltage point. A common compromise is the slope of a straight line drawn from zero voltage through the full-load point at rated voltage. For the 2500-kW generator the total flux at this point is 112.5×10^6 lines. With a leakage flux of 12%, each coil has a flux of 12.6×10^6 lines (see Table 8-2). As indicated earlier [see Eq. (8-21) and surrounding text], each coil has 192 turns and there are 10 coils in series. The field current is 39.1 A.

$$L = \frac{\phi T}{I_f} \times 10^{-8} = \frac{(12.6 \times 10^6)(192)(10)}{39.1} \times 10^{-8} = 6.2 \text{ H} \quad (8-35)$$

$$\text{Time constant} = \frac{L}{R} = 6.2/2.21 = 2.8 \text{ s} \quad (8-36)$$

This value is typical for large machines. Smaller generators have less copper in their fields and lower time constants. In cases where drive systems must have very rapid voltage adjustments, it is common to provide large forcing voltages on the field to overcome the inductive lag. These sudden excitation changes may be 4 to 10 times the IR drop of the field. This effectively reduces the time constant to one-fourth or one-tenth its normal value.

Armature-Circuit Time Constants. Compensating windings effectively lower the inductances of the armature circuit. The 2500-kW generator developed in this section has an armature-circuit inductance of 0.0001929 H and a circuit resistance of 0.00398Ω for a time constant of 0.048 s. This value is typical for large dc machines. Smaller noncompensated units have longer time constants.

8.13 TESTING

Factory Tests. These depend on the size, application, and design of the dc generator. The American National Standards Institute (ANSI) C50.4 for dc machines includes lists of recommended tests for dc generators and motors. The IEEE Test Code for dc machines covers recommended methods to be used for these tests.

8.14 GENERATOR OPERATION AND MAINTENANCE

General. Despite its rugged construction, a dc machine is a delicate device. Factory tests on large units may cost thousands of dollars and must be performed carefully to adjust the generator to obtain the best possible characteristics and commutation. Owing to shipping requirements, the generator

may then have to be disassembled and shipped in several pieces. If the final assembly is not correctly accomplished, not only have the factory tests been wasted but the machine may be damaged.

The manufacturer's instruction book should be studied carefully.

Before Installation. Upon arrival, the generator should be inspected for damage and to be sure it is dry. If it is wet, consult the manufacturer. Drying out with heat should be done only by slowly raising the generator temperature to 100°C so that moisture can escape without forming gas pockets within the insulation.

If the generator is dry and clean, the windings should be checked with a megger for insulation resistance to ground measurements. If any readings less than 1 MΩ are found, check with the manufacturer.

Alignment. After the machines are installed and grouted to the foundations, all couplings should be opened and alignments of all shafts finally checked. Regardless of whether solid or flexible couplings are used, the alignment should be as accurate as possible. The difference between the bottom and the top openings should not exceed 0.002 in for 12 in of flange diameter, and the large opening should be at the top. Regardless of the size of coupling, the difference should not exceed 0.004 in. Differences at the side should not exceed 0.001 in. Shafts should be rotated 180° and rechecked.

The frame should be set on the *magnetic center* of the core. This position can be located by setting the armature in rotation and forcing it to oscillate longitudinally the full end play of the bearing by pushing on the end of the shaft. While the rotor is coasting and oscillating freely, excite the main field. The stator can then be shifted so that the rotor position with excitation coincides with the center of bearing end play.

Air gaps between the rotor and poles should be uniform. A typical limit of variation is 0.010 in. The brushes should ride properly on the commutator surface at both extremes of bearing end play.

Prerunning Checks. The circumferential position of the brushes on the commutator is important for commutation and also to provide the voltage characteristics set at the factory. Brushes should be on the factory test setting. The toes of the brushes should be aligned and should have no skew. The spacing between adjacent arms of brushes should be identical within 0.032 in. The brushes should move freely in their holders and should have a pressure against the commutator of 2 to 3 lb/in² on the basis of brush cross section. The faces of the brushes should accurately match the curvature of the commutator surface.

The polarity of the main fields may be checked by tracing the wiring around the frame or by lightly exciting the fields and using a compass around the frame behind the poles.

The oiling system for the bearings should be checked and the oil rings tested for freedom. The entire machine, particularly its air gaps, should be inspected for foreign material.

Running Checks. Note any unusual noise as the unit is brought up to speed. Bearing temperatures should level out at acceptable values within a few hours.

The voltage should be slowly raised at no load and commutation observed. If satisfactory, the voltage should be raised to 110% of rated and then reduced.

The generator may then be loaded gradually while commutation is observed, until rated current is reached. If commutation remains satisfactory until stable temperatures are achieved, the generator is ready for work.

Shunt-Wound Generators in Parallel. A and B of Fig. 8-59 are two similar generators feeding the same bus bars C and D. If A tends to take more than its share of the total load, its voltage falls and more load is automatically thrown on B. Also, if the driver of one of the generators slows down to stop, the emf of the machine falls until the other generator starts to drive it as a motor. This continues until its driver takes over again.

The external characteristics of the two machines are shown in Fig. 8-60. At voltage E, the currents in the generators are I_a and I_b , and the line current is $I_a + I_b$. To make machine A take more of the load, its excitation must be increased to raise its characteristic curve. If a 1000-kW generator and a 500-kW machine have the same regulation curves, the machines will divide the load according to their respective capacities, as shown in Fig. 8-61.

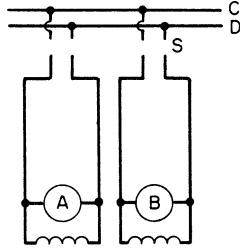


FIGURE 8-59 Shunt generators in parallel.

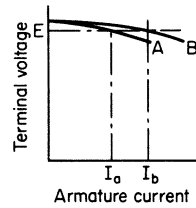


FIGURE 8-60 External characteristics of two shunt-wound generators in parallel.

Compound-Wound Generators in Parallel. *A* and *B* of Fig. 8-62 are two compound-wound machines. If *A* tends to take more than its share of the load, the series excitation of *A* increases, its voltage rises, and it takes still more of the load. Thus, the operation is unstable. If this continues until *A* takes all the load and the voltage of *B* drops to the point that *A* reverses the current in *B*, *B* will be driven as a motor. With the reversed current in the series field of *B* it becomes a differentially compounded motor, and the series weakens the flux to speed up the motor. This may progress to a point at which the unit may be damaged mechanically and electrically.

To prevent this, a bus bar of large section and of negligible resistance, called an *equalizer bus*, is connected from *e* to *f* (Fig. 8-62). Points *e* and *f* are then practically at the same potential. Therefore, the current in each series coil is independent of the current in its particular generator, is inversely proportional to the resistance of the coils, and is always in the same direction.

When a single compound generator has too much compounding, a shunt in parallel with the series field coils will reduce the current in these coils and so reduce the compounding. When compounded generators are operating in parallel using an equalizer bus, the current in the series field coils depends only on the resistance of the coils and a shunt connected across one of them is actually across all of them, reducing the compounding of all but not disturbing the relative compounding between the machines. To reduce the compounding of a single machine, it is necessary to place a resistance in series with the coils. This may require a large resistor to handle the large load current it must carry.

Maintenance. Except for the commutator and its brushes, maintenance of dc machines differs little from that of other rotating electrical machines. Proper lubrication must be provided for the bearings, and the machine must be kept clean and dry. In addition, the brushes should be checked periodically for commutation, riding ability, freedom of motion in the holders, pressure, and length.

Because the commutator necks are not insulated and receive full voltage, conducting dust from brush wear or from ventilating air can cause creepage currents between the risers and ground over insulated surfaces. To avoid this, the dc generator must be cleaned and blown out with clean, dry air at regular intervals. Air pressures above 25 lb/in² should not be used because of the danger of lifting the edges of insulating tape. The effectiveness of the cleaning program should be verified occasionally by megger readings.

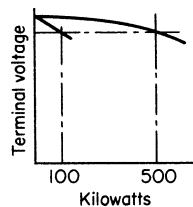


FIGURE 8-61 Division of load between two shunt generators in parallel.

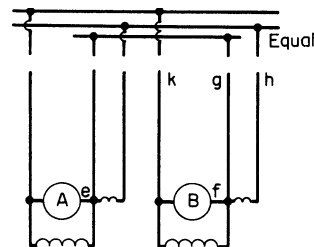


FIGURE 8-62 Compound generators in parallel.

Poor Commutation. Sparking and bar burning are usually due to one or more of the following causes:

1. *Brushes not in the proper position.*
2. *Incorrect spacing of brushes.* This may be checked by marking an adding-machine tape around the commutator.
3. *Projecting-bar-edge mica.* Mica between bars should be undercut about 0.063 in below the commutating surface, but occasionally slivers of mica are left inadvertently along the bar.
4. *Rough or burned commutator.* The commutator should be ground according to the manufacturer's instruction book.
5. *Grooved commutator.* This may be prevented by properly staggering the brush sets so that the spaces between the brushes of an arm are covered by brushes of the same polarity of other arms.
6. *Poor brush contact.* This is due to improper fitting of the brushes to the commutator surface. To seat the brushes, sandpaper should be moved between the commutator and the brush face. Emery cloth should not be used because its abrasive is conducting.
7. *Worn brushes replaced by others of wrong size or grade.*
8. *Sticking brushes.* These brushes do not move freely in their holders so that they can follow the irregularities of the commutator.
9. *Chattering of the brushes.* This is usually due to operation at current densities below 35 A/in² and must be corrected by lifting brushes to raise the density or by using a special grade of brush.
10. *Vibration.* This may be due to poor line up, inadequate foundations, or poor balance of the rotor.
11. *Short-circuited turns on the commutating or compensating fields.* These may be obvious on inspection but usually must be found by passing ac current through them for voltage-drop comparisons.
12. *Open or very high resistance joints between the commutator neck and the coil leads.* In this case, the bar at the bad joint will usually be burned.
13. *An open armature coil.* A broken coil conductor produces an effect similar to that produced by the poor joints described in the previous item. For emergency operation, the open coil may be opened at both ends, insulated from the circuit, and a jumper placed across the two affected necks. Since some sparking will probably result, operation should be limited.
14. *Short-circuited main-field coils.* With the resulting unbalanced air-gap fluxes under the poles, large circulating currents must be expected even with good armature cross connections. The offending coil may be found by comparing voltage drops across the individual coils.
15. *Reversed main-field coil.* This is an extreme case of the one described in the previous item.
16. *Overloading.*

8.15 SPECIAL GENERATORS

General. The adaptability of the dc generator for specific uses has led to the development of many special generators. These machines over the years made a significant contribution to industrial progress. However, most of these special applications have disappeared or are now being met with other devices such as silicon controlled rectifiers or programmed control of field currents to the main dc generator.

Synchronous Converters. Of all the special generators, this was one of the earlier and most widely used. It was the principal dc power source for streetcars and interurban lines. It was a most ingenious device, combining in a single armature and winding an ac motor taking its current from the lines through slip rings at the rear and a dc generator providing dc power from a commutator on the front

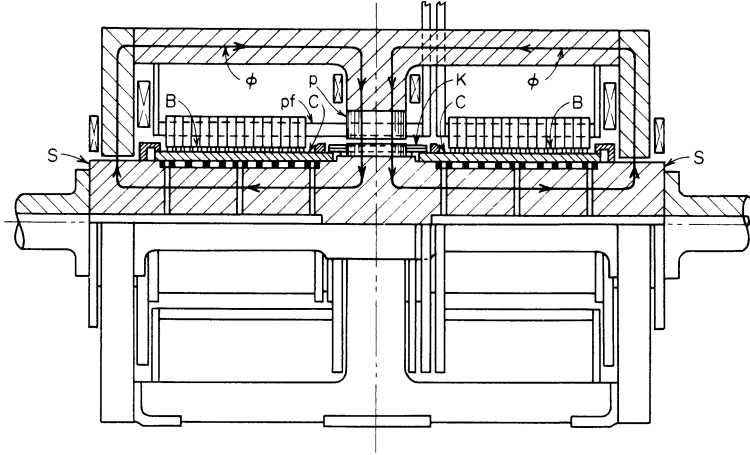


FIGURE 8-63 Brush-type homopolar generator.

end. Because the flow of the currents was in opposition, the resulting rotor winding could be small in cross section. A single stator provided flux for both functions. With the decline of street railway systems, the synchronous converter disappeared.

Rotating Regulators. These dc machines had trade names like Rototrol, Regulex, and Amplidyne. They, too, have been replaced by solid-state devices. In addition to having fields for feedback intelligence, response was enhanced using self-excited shunt fields tuned to the air-gap line or by means of cross-magnetization from armature reaction.

Three-Wire Devices. Because three-wire dc circuits are no longer in use, balancer sets and three-wire generators are relics in school labs or museums.

Homopolar or Acyclic DC Generators. The single-pole machine principle still fascinates electrical engineers and several research and development labs continue to study new arrangements of its basic parts. Fundamentally, it consists of a single conductor moving through a uniform single-direction flux with a collector at each end of the conductor. The output is a steady ripple-free pure dc current and no commutation. Currents reaching 270,000 A at 8 V were provided by one commercial unit shown in Fig. 8-63. Recent efforts have been mainly to use liquid metals to take the large currents from the rotating collectors and to obtain higher voltages by connecting units in series. Some success has been possible, but restricting the sodium potassium to the collector area has proved difficult.

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